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RESEARCH AND DEVELOPMENT OF ANTI-G LIFE SUPPORT SYSTEMS:

Part 1. Development and Evaluation of Uniform-Pressure Anti-G Suits

AD-A185 658

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NOTICES

This final report was submitted by the Life Sciences Division, Technology Incorporated, 300 Breesport, San Antonio, TX 78216, under contract F33615-81-C-0600, job order 7930-14-42, with the USAF School of Aerospace Medicine, Human Systems Division, AFSC, Brooks Air Force Base, Texas. Larry J. Meeker (USAFSAM/VNS) was the Laboratory Project Scientist-in-Charge.

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The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 169-3.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A skin pressure measuring device was designed and fabricated to measure pressure actually applied to the lower body during anti-G suit inflation. This device was used with a variety of developmental uniform-pressure anti-G suits; basketweave, multiple-capstan, and reticulated-foam suit designs were evaluated. Results indicated that owing to engineering incompatibilities involving weight, bulk, sizing, fitting, and effective pressure loss attributable to friction between the interdigitized tapes, the capstan approach is not a practical solution to developing a uniform-pressure anti-G garment. The reticulated-foam approach shows promise because of a tendency to retain its original shape when pressurized to high pressures. Further development of reticulated-foam anti-G designs is recommended.

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RESEARCH AND DEVELOPMENT OF ANTI-G LIFE SUPPORT SYSTEMS:

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INTRODUCTION

The Crew Technology Division of the USAF School of Aerospace Medicine (USAFSAM/VN) is responsible for developing, testing, breadboarding, evaluating, and recommending methods of protecting aircrews against hazardous effects of high-G environments, and for preventing possible cumulative effects of exposure to acute, chronic, and repetitive high-G conditions over the career-spans of individual aircrew members.

Technological advances which improve physiological tolerance to high sustained G (HSG) lead to expanded operational limits as well as to increased protection of personnel. Modern high-performance fighter aircraft are capable of achieving ever-increasing sustained acceleration profiles. The ability of the human body to withstand this acceleration has become the critical factor determining the limits of modern air weapons systems capabilities. This problem of human tolerance to the G levels associated with the new acceleration profiles has reemphasized the need for improved pilot protection techniques.

The use of the anti-G suit, as the primary source for increased G-tolerance protection, has been reexamined by USAFSAM. Potential design improvements to existing anti-G suits, as well as possible new suit design concepts, have been developed and evaluated within the scope of this project.

OBJECTIVES

The principal overall objectives of work performed on contract F33615-81-C-0600 have been: (1) to perform research, development, testing, and evaluation (RDT&E) aimed at improving performance of anti-G suits, including modification of existing designs and development of new designs; (2) to perform research on mechanisms and management of decompression sickness (DCS); (3) to develop, manage, and maintain physiological data bases relevant to decompression sickness and acceleration effects (reported separately as USAFSAM-TR-86-37); (4) to develop a computer model for measurement of stress on a pilot's head and neck caused by above-the-neck life support equipment at G; (5) to update USAFSAM human centrifuge graphics; and (6) to compare performance of current and prototype anti-G valves.

To accomplish these overall objectives, we designed a number of discrete research tasks. These tasks are summarized, and task relationship to overall objective is indicated in Table 1. Results of efforts on each of these tasks have been described in a final report, of which this is Part 1. Part 1 details work performed relevant to objective (1): RDT&E directed toward improvement of performance of anti-G suits.

TABLE 1. SUMMARY OF SPECIFIC ALSRAD TASKS PERFORMED ON CONTRACT F33615-81-C-0600

Task	Description	Report Part
	Anti-G Suit Performance	
1	RDT&E and fabrication of a skin pressure measuring system	1
2	RDT&E of uniform pressure anti-G suit	1
	Decompression Sickness Research	
3	Research on mechanisms and management of DCS	
	3.1 R&D of bends-screening index for crew selection, high-altitude/space missions	2
	3.2 Research on decompression sickness model systems	2
	3.3 Definition of minimum for zero-breathe pressure	2
	3.4 7.8 psi study	2
	Physiological Data Base Systems	
4	Development/management of repositories for acceleration and decompression sickness research data	*
	Pilot Head/Neck Stress	
5	Development of computer model for measurement of stress on pilot's head/neck for above-the-neck aircrew life support equipment	**
	Human Centrifuge Graphics Systems	
6	Updating of USAFSAM human centrifuge graphics	3
	Anti-G Valve T&E	
7	Comparison of current and prototype anti-G valve performance	4

* Published separately as USAFSAM-TR-86-37
** Informal report to Contract Monitor

EQUIPMENT AND PROCEDURES

Equipment

Task 1 - Skin Pressure Measurement

Liquid-filled Test Bladder - A small liquid-filled test bladder that was continuously monitored with a pressure transducer was used in preliminary studies. The measurement system is shown schematically in Figure 1. The test bladder was the crucial element of this system. A bladder extracted from an infant blood pressure cuff (W. A. Baum Co., Inc., Copiauge, New York) was used. The system was liquid volume-sensitive and initial experiments indicated 1.5 ml water to be optimal for the required measurements.

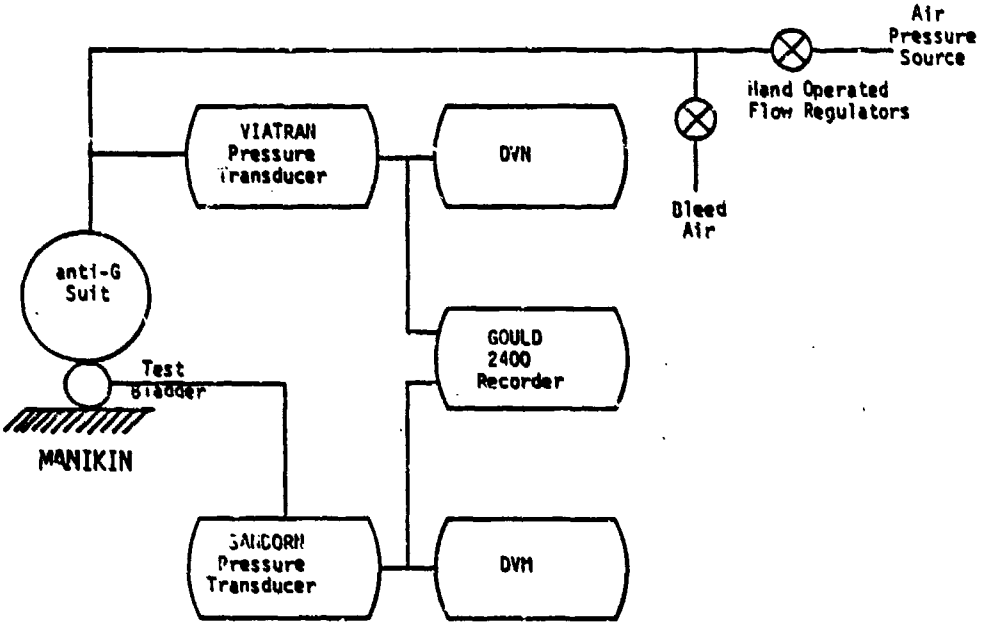


Figure 1. Skin pressure measurement system.

Pneumatic Switch Skin Pressure Tracking System - The Pneumatic Switch Skin Pressure Tracking System (PSSPTS) is shown schematically in Figure 2. The focal element of the system is a flat, pneumatically actuated switch which is placed under the anti-G suit. Air pressure in the switch holds the circuit open until equaled or exceeded by the applied skin pressure. This technique is an adaptation of one reviewed earlier (5). The original technique, however, had a serious inherent objection in the time required to make a measurement. This objection was overcome by automating the entire system

Pneumatic Control Device - The Pneumatic Control Device (PCD) is shown in Figure 3. This chassis contains solenoids, flow controls, and associated plumbing for all three pressure switches. The pneumatic and electric schematic for the PCD is shown in Figure 4.

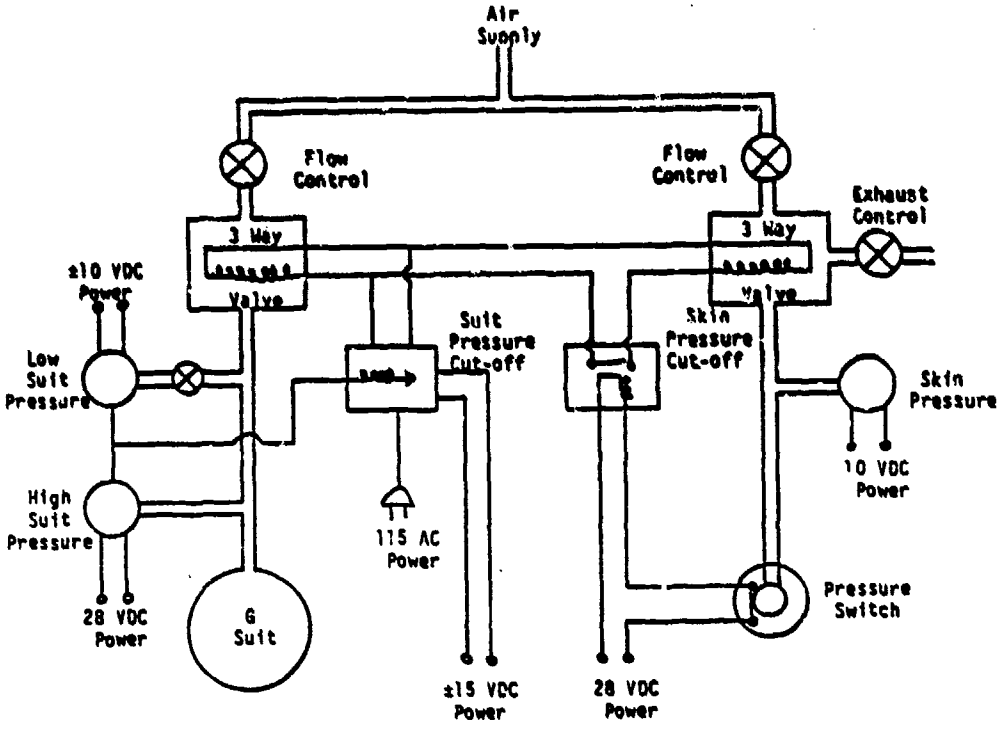


Figure 2. Pneumatic switch skin pressure tracking system.

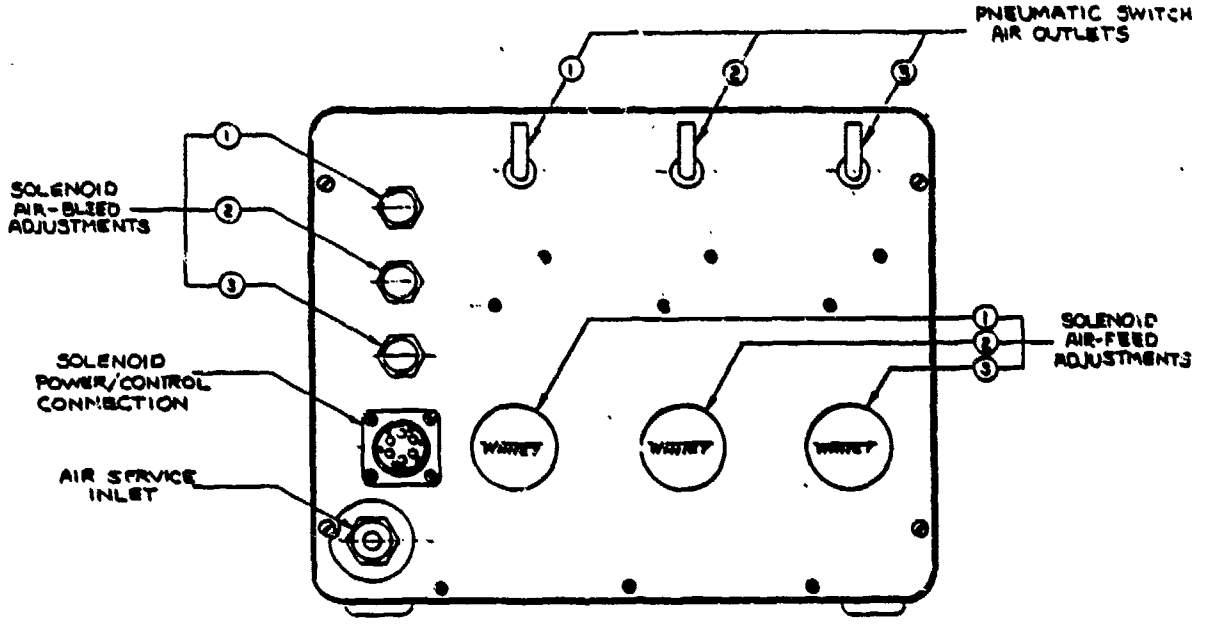


Figure 3. Multi-channel skin pressure measurement system pneumatic control device.

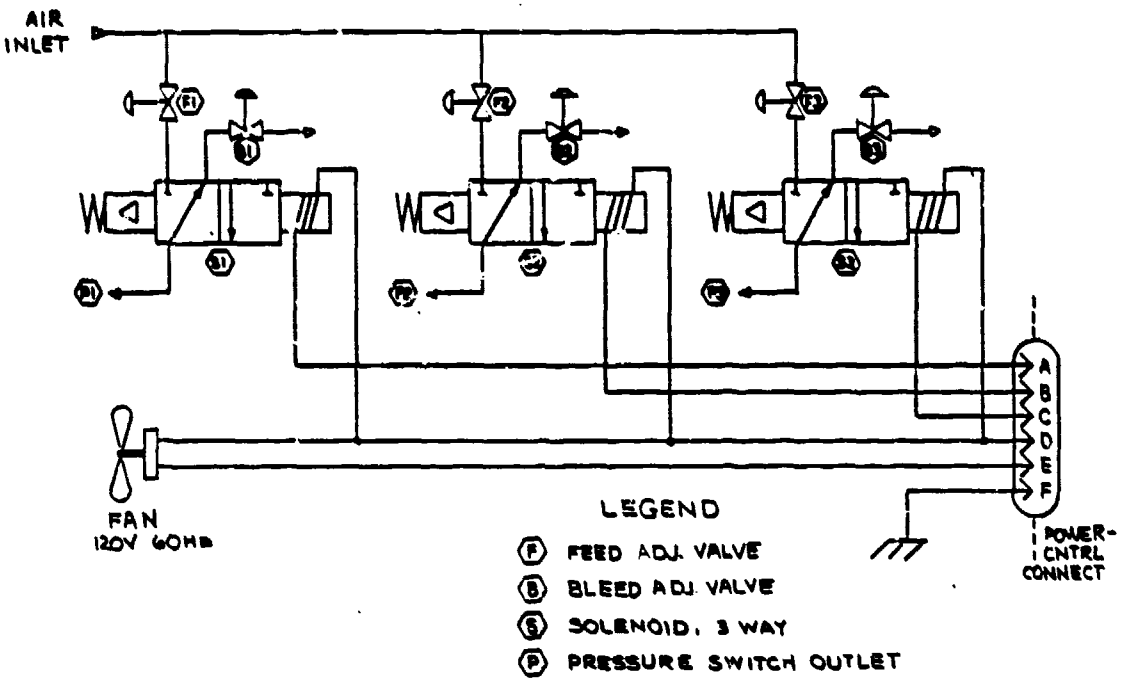


Figure 4. Pneumatic control device schematic.

Electronic Control Device - The electronic control circuitry and amplifiers for the skin pressure measurement system are contained in the Electronic Control Device (ECD) (Figs. 5 and 6).

The chassis schematic is shown in Figure 7. The transducer plugs (i.e., T1 through T3, Fig. 7) are attached to the 3 Statham P23Db pressure transducers mounted in the pressure transducer housing (not shown). The 3 printed circuit board connectors (i.e., VB1 through VB3) provide a mechanical interface with the pressure switch control circuit boards. The solenoid connecto (SOL) interfaces with the PCD, while the function of the pressure switch (PRESS SW), alternating current power (AC), direct current power (DC), and output connectors is self-explanatory. The function of each connector pin is shown in Table 2.

Procedures

Development of procedures was integral to the development of the systems described here. Procedures for each system are therefore described in the appropriate subsection of the Results section.

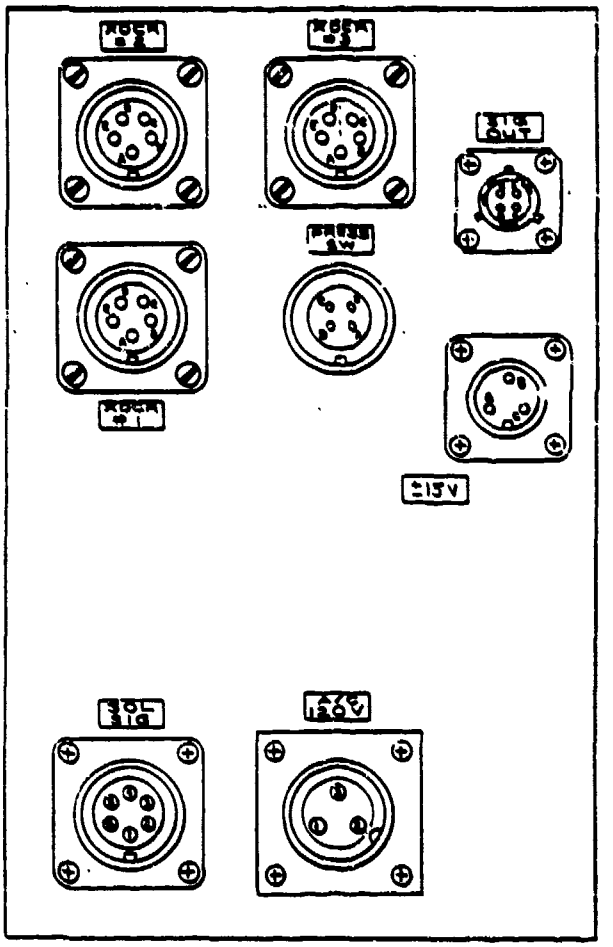


Figure 5. Multi-channel skin pressure measurement system electronic control device (front view).

RESULTS

Task 1 - Skin Pressure Measurement

An anti-G suit functions by applying pressure directly to the skin to counteract gravitational forces. Therefore, to evaluate performance of an anti-G suit, it is essential to verify and measure the actual transfer of pressure from suit to skin.

Technology Incorporated conducted exhaustive studies of skin pressure measurements under a capstan suit in an earlier program (5). For this work, strain gages were mounted as force gages and the data empirically converted to appropriate pounds per square inch (psi) readings. While this technique provided useful data, it possessed several disadvantages. The most serious problem was the indirect measurement and interference with the measured environment.

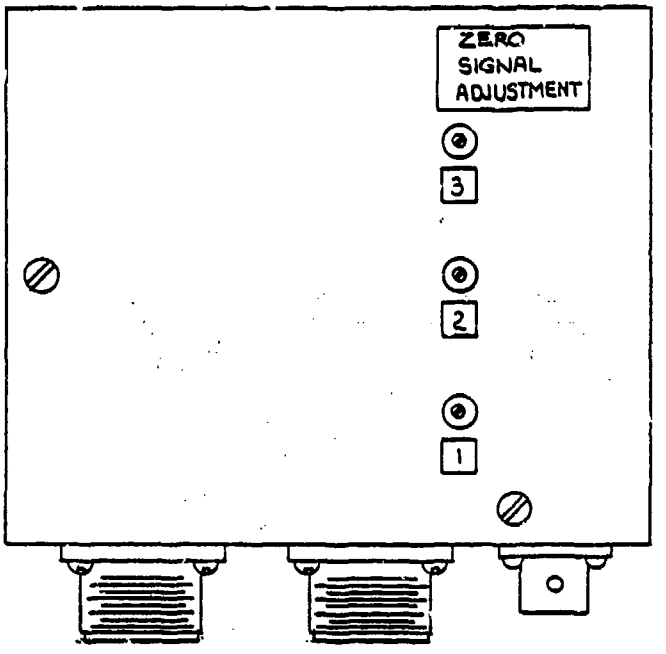


Figure 6. Electronic control device (top view).

Liquid-filled Test Bladder

A revised skin pressure measuring technique was developed to overcome these disadvantages. This revised technique is an adaptation of the approach described in a similar study performed for National Aeronautics and Space Administration (NASA) by General Electric Co. (3). In this previous study, a small pneumatic bladder was inflated until pressure equalization was detected and the test bladder pressure recorded. However, it was suggested that the time required by this sampling approach might make human testing very uncomfortable, especially at high suit pressures.

Several sources of error were encountered in development of this technique. First, the liquid-filled bladder technique will generally measure the minimum pressure exerted on the bladder, excluding obstructions and over-filled conditions. In those cases where the perpendicular pressure on the test bladder is not uniform, such as along the edge of a suit bladder, the higher pressure will force the liquid beneath it into a lower pressure area. The resulting liquid pressure will tend to assume the same pressure as that exerted in the lower pressure area.

Second, the liquid bladder technique does tend to measure higher pressure as the volume of water in the bladder is increased. This phenomenon has been dubbed the "tenting effect" and is represented in Figure 8 at point C. In this case, the fluid in the bladder increases its interference with the measured environment by elevating the suit bladder surface. When enough tension occurs in the suit bladder skin, there is a tendency to bridge between points, leaving a void as shown at point C (Fig. 8). The fluid pressure on the suit bladder skin over the voided area produces a resultant force which is translated to the test

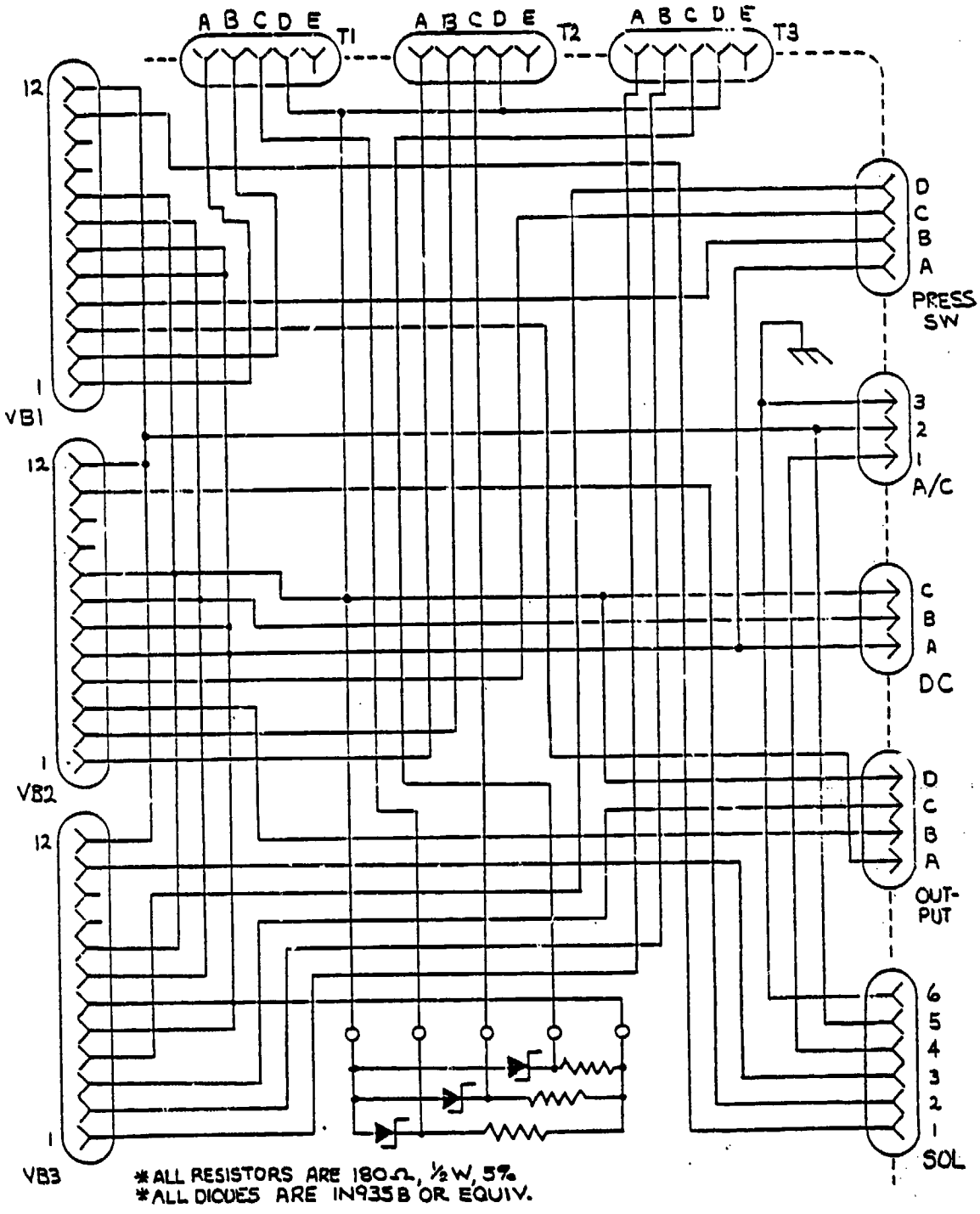


Figure 7. Electronic control device chassis schematic.

TABLE 2. ELECTRONICS CONTROL DEVICE PIN ASSIGNMENT

Connector	Pin	Function
T 1,2,3	A	+ Signal
	B	- Signal
	C	+ 10 VDC
	D	Ground
	E	Open
VB 1,2,3	1	Pressure XDCR + signal
	2	Pressure XDCR - signal
	3	Pressure signal out
	4	Pressure switch (+15 VDC)
	5	Pressure switch return
	6	+ 15 VDC (VCC)
	7	- 15 VDC (VEE)
	8	Instrument ground
	9	Open
	10	Open
	11	115 VAC hot (Blk)
	12	115 VAC rtn (Wht)
PRESS SW	A	Pressure switch (+15 VDC)
	B	Pressure switch #1 return
	C	Pressure switch #2 return
	D	Pressure switch #3 return
AC	1	115 VAC common (Wht)
	2	115 VAC hot (blk)
	3	Ground (GRN)
DC	A	+ 15 VDC
	B	- 15 VDC
	C	Ground
Output	A	Pressure signal #1 output
	B	Pressure signal #2 output
	C	Pressure signal #3 output
	D	Ground
Sol	1	Solenoid #1 control
	2	Solenoid #2 control
	3	Solenoid #3 control
	4	115 VAC common
	5	115 VAC fan
	6	Ground

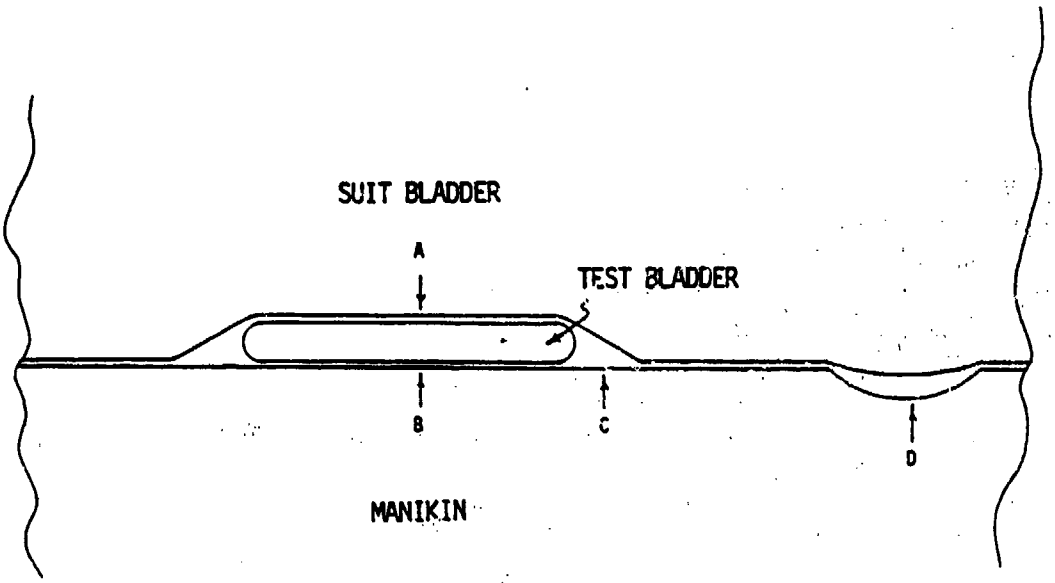


Figure 8. Pneumatic pressure interface.

bladder by suit bladder skin tension. Point D represents a special case of the "tenting" effect (Fig. 8). In this case, the opposing surface (i.e., the manikin) changes are sharp enough to cause bridging. This special case is important when considering the uniformity of pressure distribution along and around the limb.

Pneumatic Switch Skin Pressure Tracking System

Another skin pressure measuring technique was subsequently developed which resulted in improved measurements. This technique was the Pneumatic Switch Skin Pressure Tracking System (PSSPTS).

The PSSPTS technique has the advantage of minimizing the "tenting" effect described previously. The switch construction consists of two wires attached to two sections of polyurethane-impregnated nylon taffeta (anti-G suit bladder material). The taffeta sections are sealed at the edges to create a small bladder. When the bladder is completely deflated, two wires touch, closing a circuit.

The PSSPTS performs two simultaneous functions. First, it automatically inflates the anti-G suit. Second, it automatically tracks skin pressure by repetitiously inflating and deflating the pneumatic switch section. When the circuit is initiated, the anti-G suit inflation is started at a controlled rate which results in inflation to maximum pressure in 30 s. A special circuit monitors the suit pressure, and at a preset suit pressure level (i.e., 8 psig or 40 psig), automatically stops suit inflation and starts suit deflation.

Skin pressure measurements are made by automatically inserting a bolus of air into the switch each time the switch circuit is closed. When the circuit opens, the pressure is released at an adjustable rate. Each time the applied skin pressure equals internal switch pressure, the switch circuit closes and the cycle is repeated.

Data charts of skin pressure measurements (Fig. 9) record a ramp function representing the G-suit pressure, and a saw-tooth shaped trace of internal switch pressure. The minimum values of the saw-tooth curve represent the pressure at which equalization of switch pressure and skin pressure resulted in switch closure (Fig. 9).

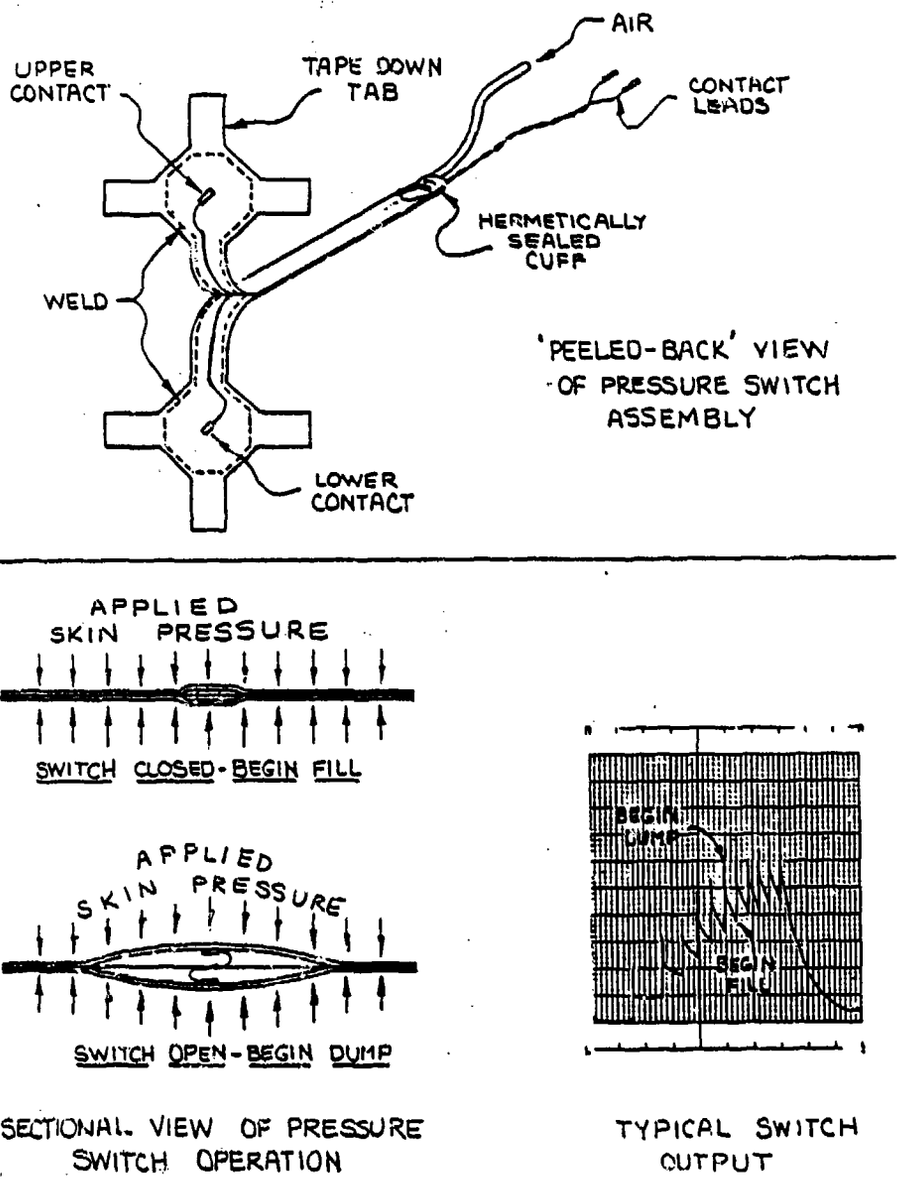


Figure 9. Skin pressure switch.

Data obtained from a typical PSSPTS experiment are displayed in Figure 10.

Sampling points were:

C - right lower leg front
F - right upper leg front or top
I - right upper leg inside
O - right upper leg outside
R - right upper leg rear or bottom

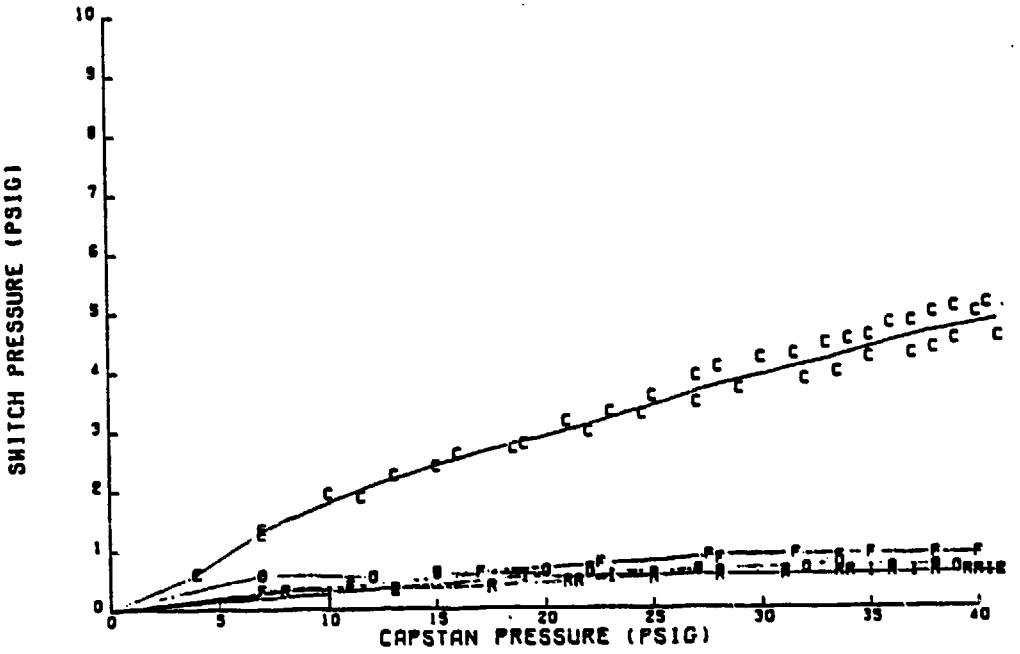


Figure 10. Subject 2 switch pressure (front, rear, inside, outside and calf) vs. capstan pressure.

Evaluation of prototype anti-G garments during Phase II employed a three-channel skin pressure measurement system. The design of this system was based upon the pneumatic switch concept, developed and prototyped during Phase I. This three-channel design allowed simultaneous measurement and recording of three different skin pressure loci on a test subject in the gondola under elevated G conditions. The three switches were attached to the test subject by means of adhesive tape before donning of the G-suit. Once the subject was seated in the gondola, pneumatic and electrical connections of each switch were made with the calibrated control system hardware in the gondola (Figs. 11 and 12). This system provided a continuous record of abdominal, thigh, and calf skin pressures.

A pressure switch calibration fixture was designed and constructed. This fixture is a specially formed bladder of urethane-coated nylon oxford fabric, designed to apply pressure to the switch with direct and uniform distribution of force.

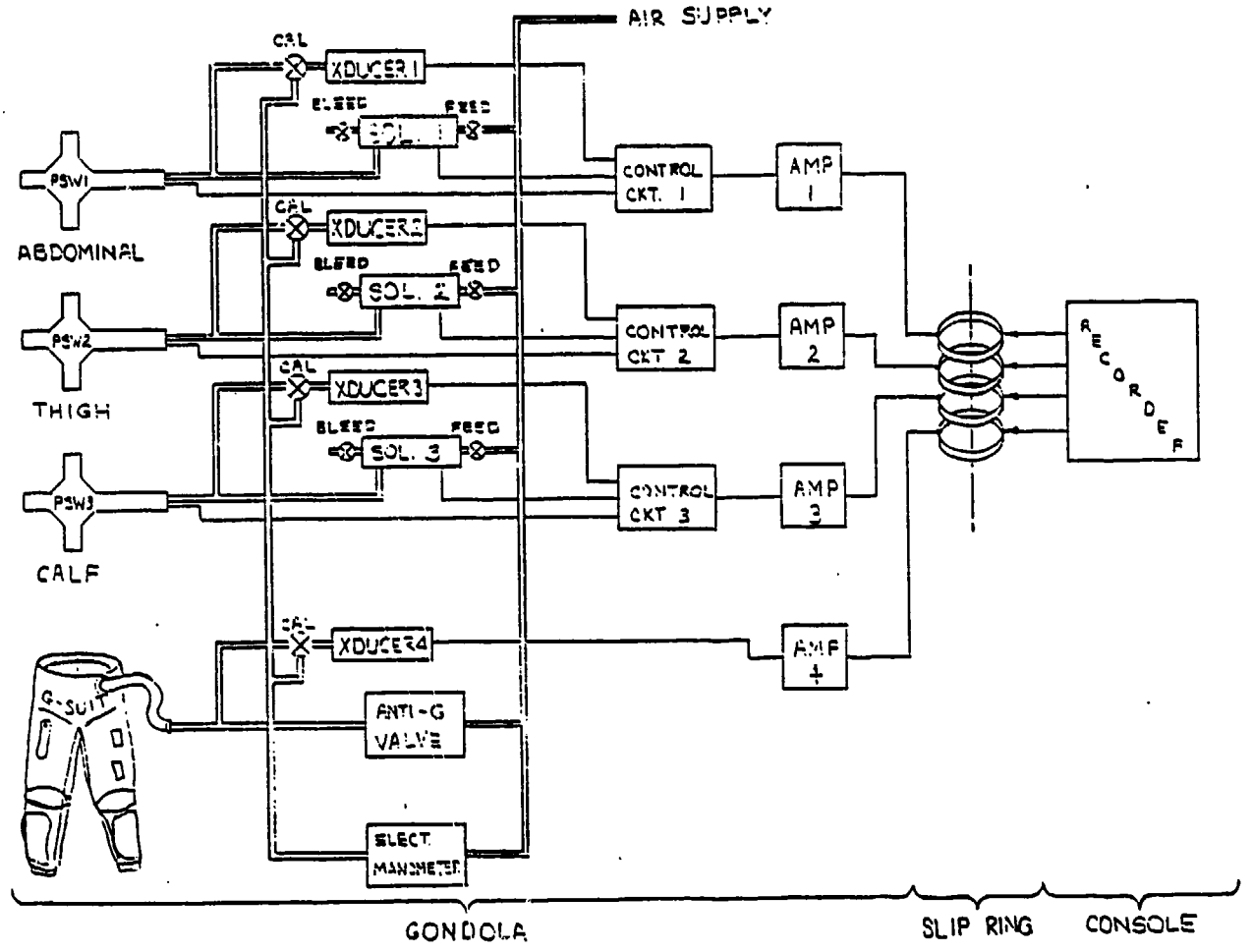


Figure 11. Skin pressure measurement system.

Assembly and Calibration of Skin Pressure Measurement System

Each skin pressure switch was assigned a number and labeled. Each electrical lead and air hose associated with that switch was also labeled with the switch number. Each switch was assigned to a specific solenoid, transducer, and control circuit channel. Connection points for all related electrical and pneumatic hook-ups in the gondola were correspondingly labeled with the appropriate channel number. Each channel output was assigned to a specific amplifier, slip ring, and recorder channel. Once the system was set up, changes in component channel assignments were avoided.

For prerun calibration of the system, each transducer was plumbed in such a manner as to allow application of a calibrated air pressure from the Datametrics electronic manometer. Each transducer/recorder channel (including G-suit pressure transducer) was zeroed and calibrated against 0 and 10 psig (full range), respectively. An intermediate pressure of 5 psig was used as a linearity check. After each transducer/recorder channel was zeroed and calibrated, the transducer valve was switched from the manometer back to its assigned pressure switch.

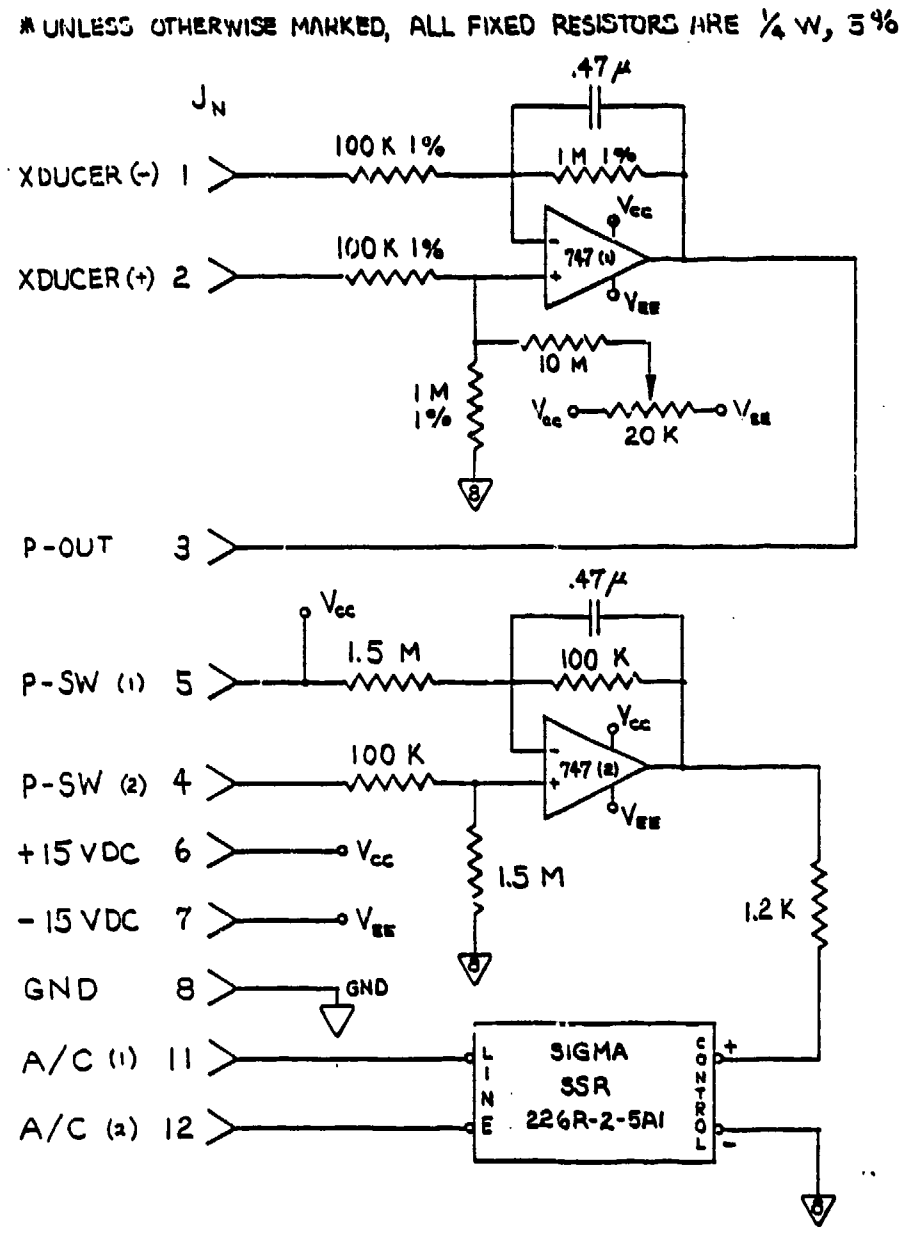


Figure 12. Pressure switch control circuit.

Each pressure switch was calibrated under dynamic conditions, preceded by a standard prerun transducer/recorder calibration. The pressure switch calibration fixture was connected to the standard anti-G valve in the gondola. Pressure switch No. 1 was then inserted into the fixture and securely placed in the gondola seat. After accomplishing the proper adjustment of feed and bleed rates, switch and fixture were exposed to a variety of acceleration profiles. These profiles included a 0.1 G s^{-1} onset ramp, a 0.5 G s^{-1} onset ramp, and a 1 G s^{-1} onset ramp up to 9 G. Furthermore, the switch rode a 5-min SACM-2 profile. This procedure was repeated for switches Nos. 2 and 3.

Data from each switch were recorded, identified, transcribed into tables, entered into computer reference files, and plotted to show switch pressure vs. fixture (i.e., suit) pressure. Each profile was evaluated for linearity and bias. In event of a switch failure, a replacement switch was calibrated as outlined.

Switch placement was as follows:

Switch no.	Location
1	Abdomen - anterior surface at umbilical plane and inferior to umbilicus
2	Right thigh - anterior surface, midway between knee and crotch
3	Left calf - posterior surface at maximum diameter.

The skin pressure measurement system was packaged into three chassis, suitable for use in the USAFSAM human centrifuge.

Considerable effort was expended to assure that the pressure switch system accurately measured actual pressure applied to the subject's skin. One factor influencing skin pressure which was difficult to control during calibration, was the radius of the surface to which pressure is applied. This problem was solved with development of a calibration fixture (Fig. 13). This fixture is inflated slowly, presenting a nearly ideal (i.e., uniform fluid) pressure envelope around the pressure switch. The fixture design was intended to eliminate radius and tenting effects, allowing characteristics of the pressure switch and system to be identified. This design allowed other physical effects of skin pressure application to be evaluated.

A plot of switch pressure data from all three pressure switches vs. calibration fixture pressure yields a linear relationship (Fig. 14). A reasonable prediction of skin pressure can be derived from the equation of the line obtained:

$$Y = 0.95X + 0.71$$

where Y represents actual skin pressure and X represents pressure in the switch. Figure 15 is a scatter plot of error magnitude and frequency between actual values observed and values predicted by this equation. It appears that skin pressure may be predicted within $\pm$ 0.2 psig 90% of the time.

The effect of G-level on switch pressure was then examined. For each of three different G-levels (+1 G_z, +5 G_z, and +10 G_z), three runs for each switch were undertaken. These data are shown in Figures 16 through 19. We predicted that there would be no significant differences in switch pressure for different G-levels, because of the orientation of the measuring devices with respect to

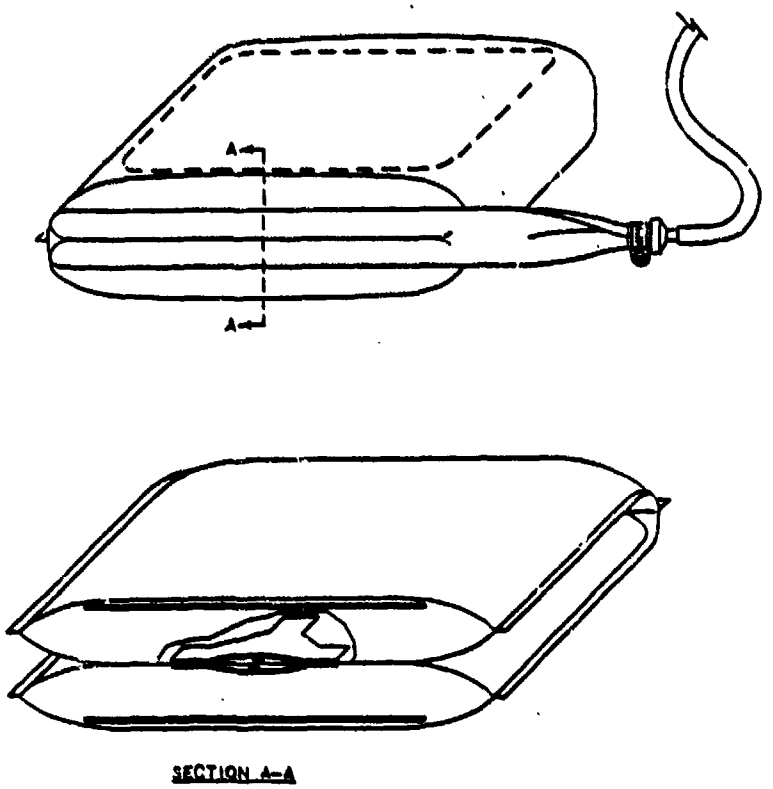


Figure 13. Pressure switch calibration fixture.

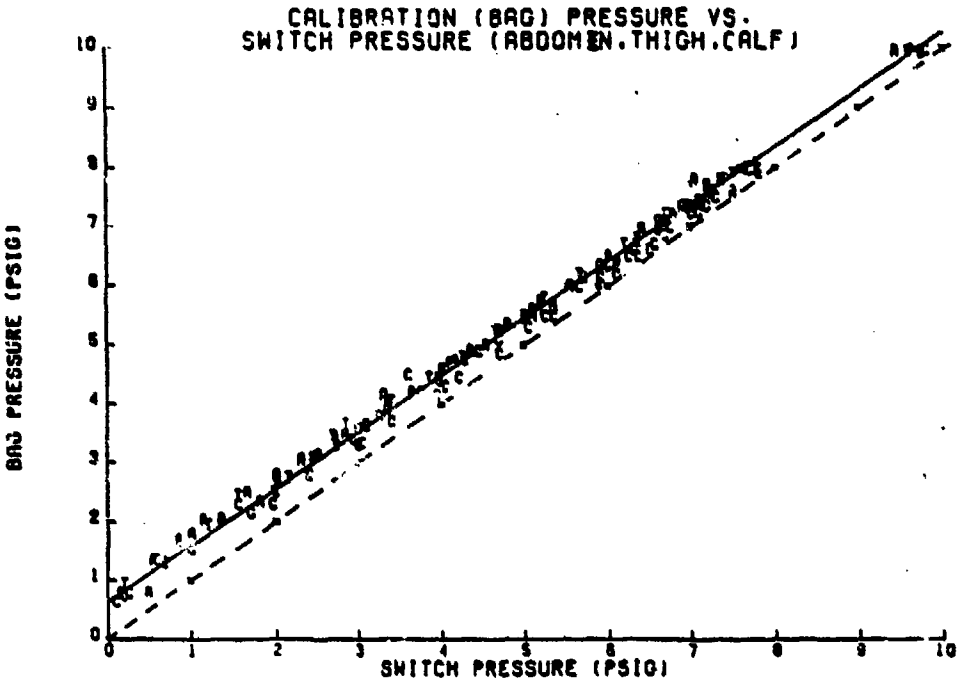


Figure 14. Calibration (bag) pressure vs. switch pressure (abdomen, thigh, calf).

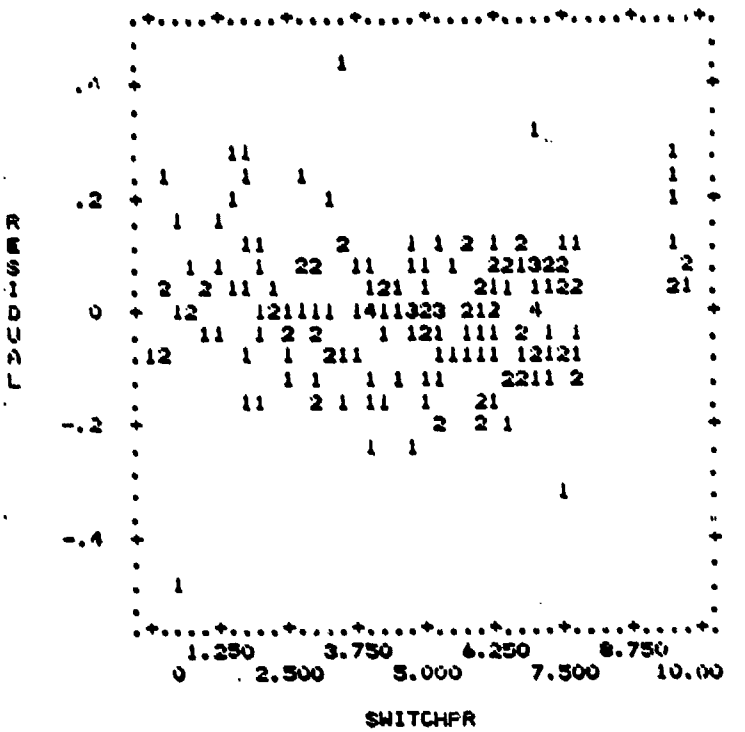


Figure 15. Error of predicted skin pressure compared to observed skin pressure.

gravitoinertial force. Using BMDP statistical program P3D, independent t-tests were performed between switch pressures at +1 G_z and +5 G_z, +5 G_z and +10 G_z, and +1 G_z and +10 G_z. None of these statistical tests indicated any significant differences in switch pressure for the different G-levels:

G-levels compared	t(196) value	p
1 G_z x 5 G_z	0.32	> .05
5 G_z x 10 G_z	0.79	> .05
1 G_z x 10 G_z	0.48	> .05

Results of these statistical analyses support the hypothesis that the range of G-levels investigated does not affect switch pressure.

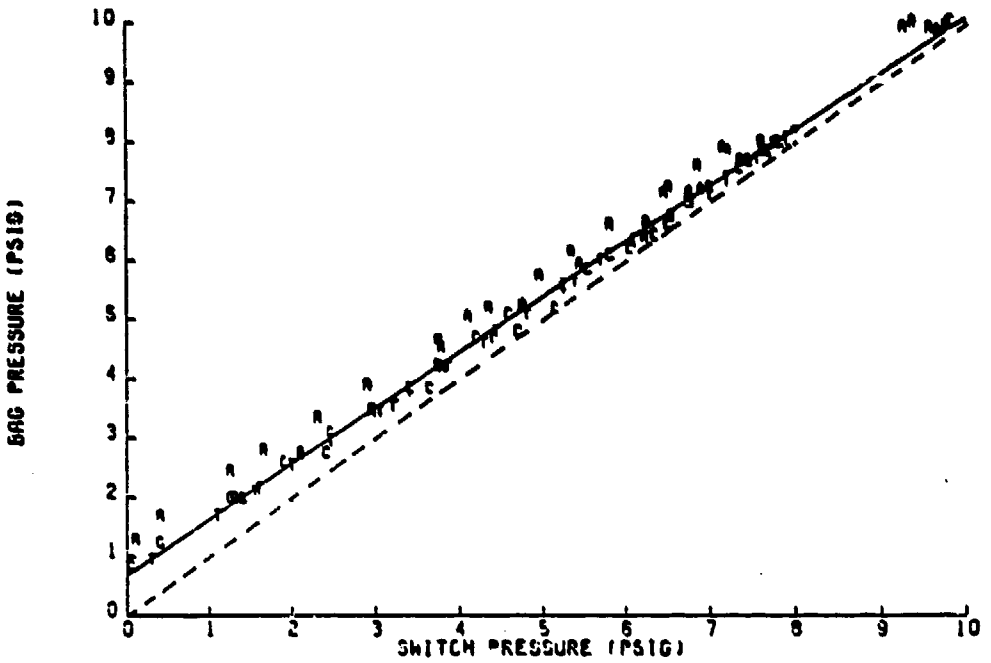


Figure 16. Bag pressure vs. switch pressure (abdomen, thigh, calf) at 1 G.

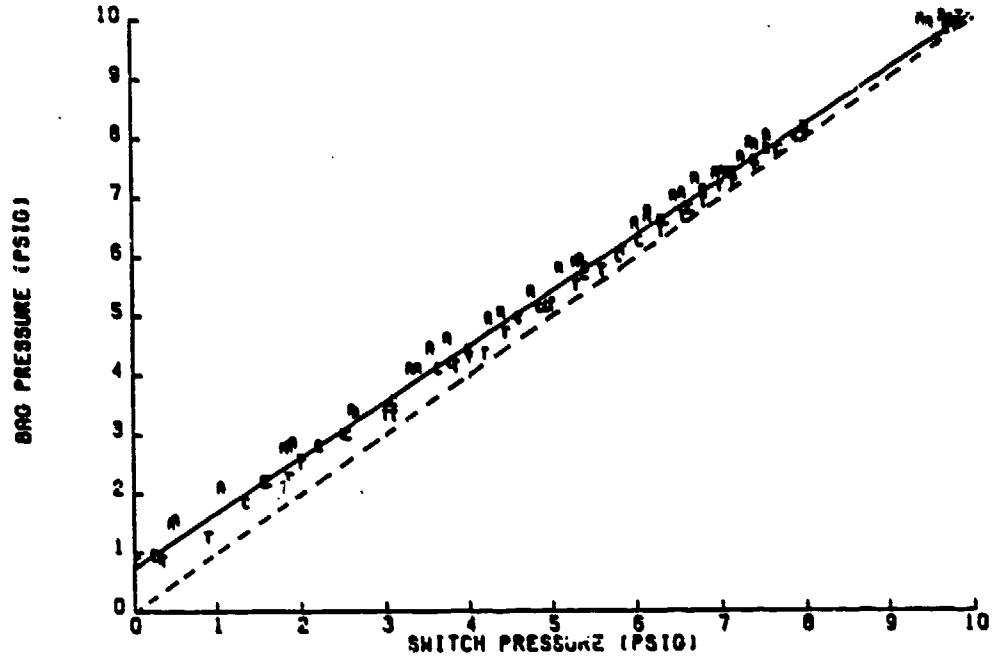


Figure 17. Bag pressure vs. switch pressure (abdomen, thigh, calf) at 5 G.

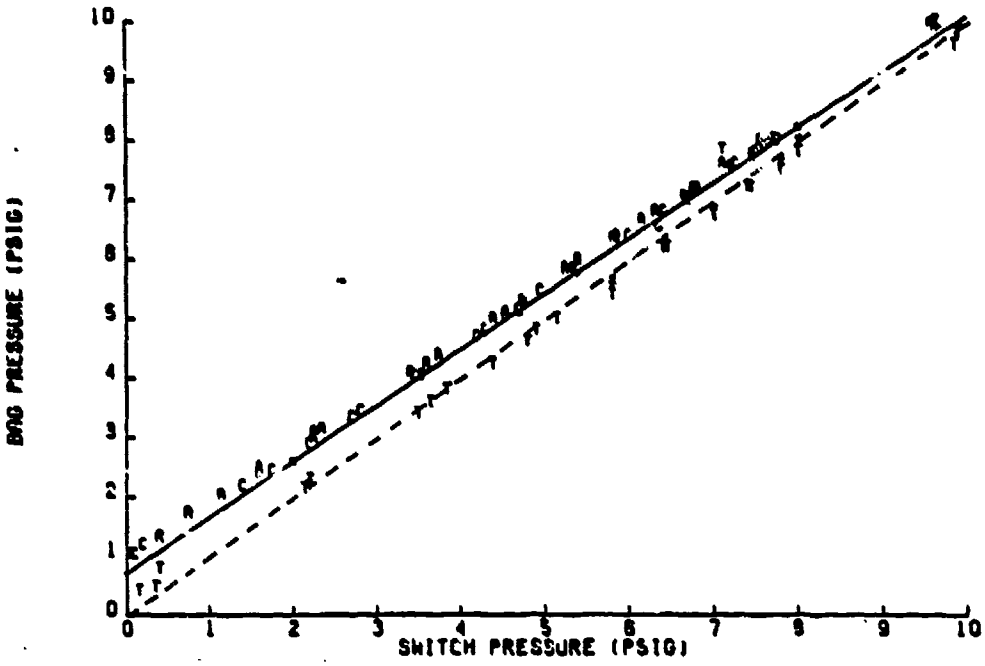


Figure 18. Bag pressure vs. switch pressure (abdomen, thigh, calf) at 10 G.

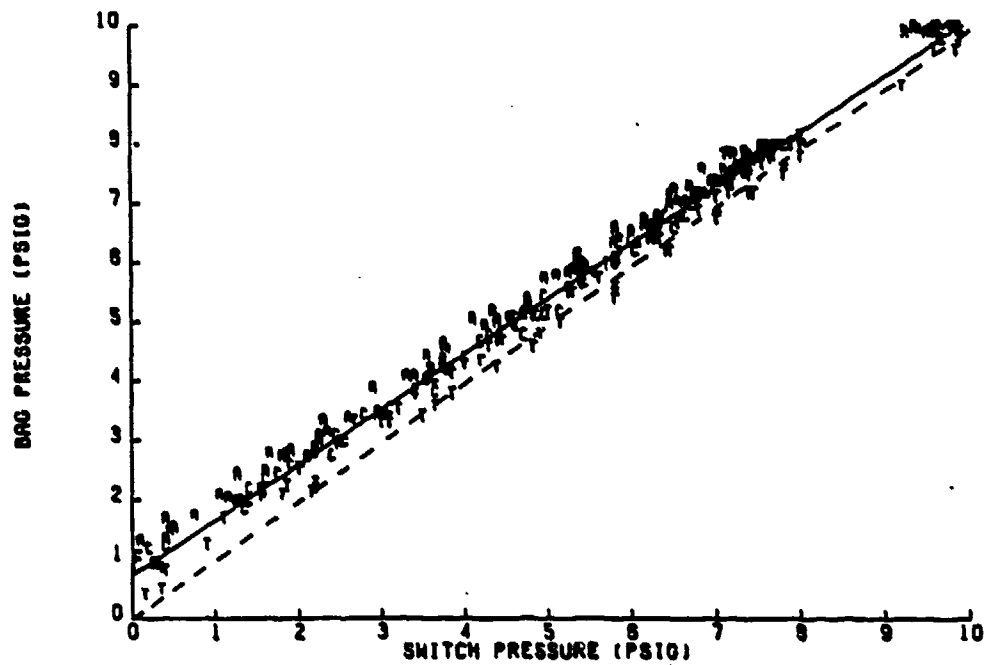


Figure 19. Bag pressure vs. switch pressure (abdomen, thigh, calf) at all G levels.

Task 2 - Uniform Pressure Anti-G Suit

A study by Shaffstall and Burton (4) indicated that a uniform pressure suit (UPS) would ". . . increase both straining G-tolerances and relaxed $+G_z$ tolerances. We estimate that, in comparison with the five bladder suit, the UP suit provided an improvement in relaxed tolerance of at least +1.4 G_z . . ." That same report defined a UPS as one ". . . which applies pressure evenly around the circumference of the leg . . ." The suit used in that study used the pneumatic lever, or capstan, principle for application of pressure to legs and pelvic region.

Development of a new anti-G suit based on the uniform pressure (UP) concept was initially approached by modification of existing capstan (pneumatic lever) designs. Subsequently development of a unique technique, reticulated foam, was initiated for uniform pressure application.

The pneumatic lever suit is an old concept; it has undergone RDT&E for approximately 35 years. Although improved G-performance capabilities have been demonstrated for such a suit, several disadvantages have prevented its acceptance as standard USAF equipment. Most of these disadvantages involve pilot comfort. The pneumatic lever design was also rejected by NASA (2) as a viable approach because of poor pilot acceptance. Our approach to a UPS design, therefore, considered both favorable and unfavorable aspects of present pneumatic lever designs.

Initial guidelines established for conduct of this RDT&E project were:

1. Don't reinvent the wheel.
   A limited review of literature on anti-G suit research over the last 40 years was undertaken to avoid duplication of effort, and to gain insight into desirable characteristics of a UPS.

2. Document physical parameters reported to be associated with improved UP anti-G suit performance by review of literature of previous pneumatic lever and five-bladder suit tests; and actual measurement of physical parameters involved (skin pressure).

3. Develop new suit concepts. This effort was designed to incorporate major advantages of pneumatic lever and bladder type G suits while circumventing prominent disadvantages of each.

Standard Capstan Suit Modification

A major objection to the "standard" capstan anti-G suit described by Shaffstall and Burton (4) is the requirement for two pressure (0-10 psig and 0-50 psig) sources. An obvious modification to that system would be a device that would create a second pressure profile from the first. The approach taken here was to locate a passive proportional pressure regulator available commercially. A market search was undertaken by querying a broad cross-section of

appropriate manufacturers. Each letter briefly explained the application desired, and included a drawing similar to Figure 20. Several manufacturers responded with offers to develop such a device; however, none indicated any similar device already in manufacture. This concept was not pursued any further.

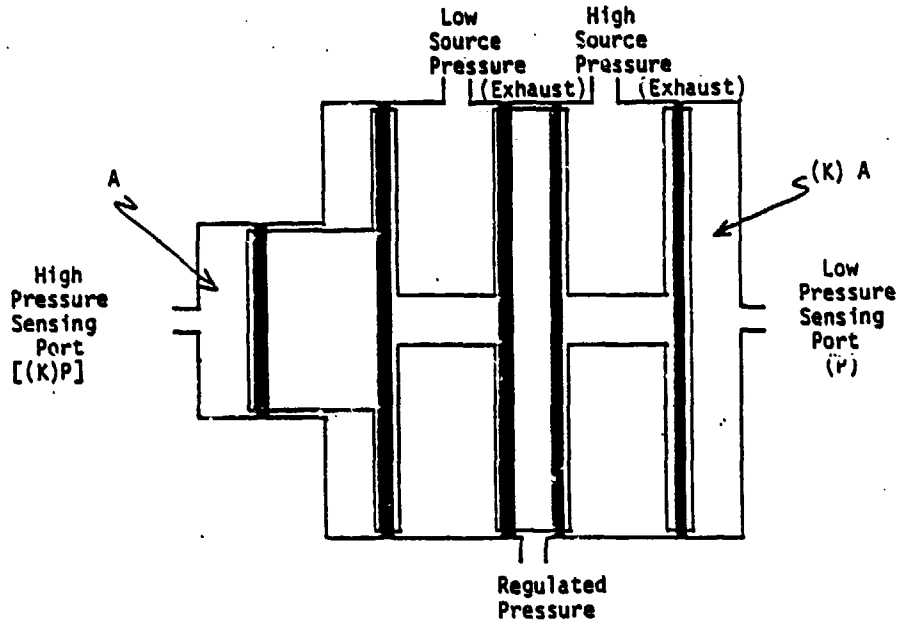


Figure 20. Ratio (K) pressure regulator.

Multiple Capstan Suit

The multiple capstan breadboard allowed for six capstan tubes. The design was intended to provide a one-to-one pressure transfer (i.e., 1 psig skin pressure for 1 psig capstan pressure).

Each capstan tube had a diameter of 2.8 cm (1.1 in.) at 1 psig when mounted on a manikin with a thigh circumference of 50.8 cm (20 in.) and diameter 16.5 cm (6.5 in.).

Skin pressures resulting from this system are shown in Figure 21. Data from locations directly under the capstan tubes (front of leg) and from the back of the leg, exhibited approximately one-half theoretically expected magnitudes. Data from locations on interior and exterior thighs were from one-eighth to one-fifth expected theoretical values. This effect was first attributed to local radius effects, so a separate test was run using a uniform radius (i.e., mounting the test section on a cylinder). Results of this test are shown in Figure 22. In this case, limb diameter was 14.29 cm (5.625 in.) and capstan tube diameter was 3.18 cm (1.25 in.) for a theoretical capstan skin pressure ratio of 4.5. indicating that skin pressures on the inside and outside are still reduced.

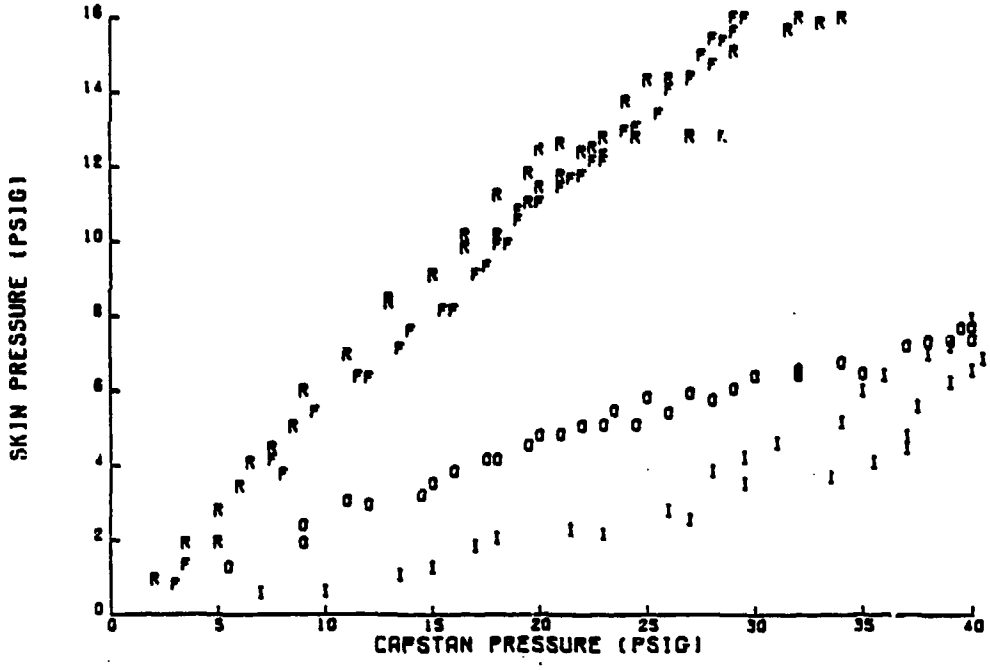


Figure 21. Manikin skin pressure under a low-pressure capstan section.

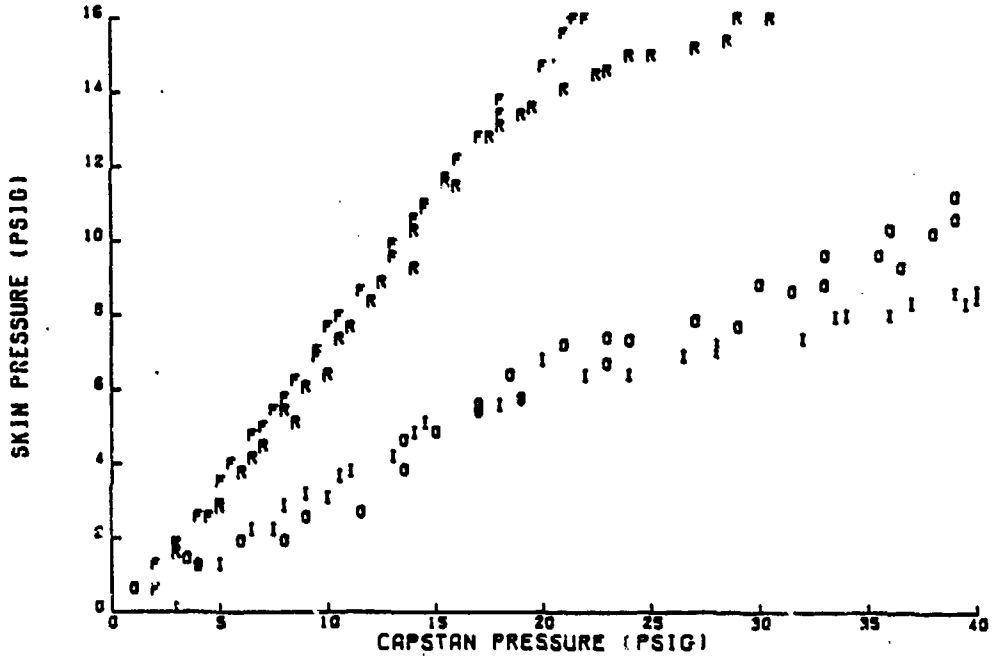


Figure 22. Skin pressure under low-pressure capstan section on uniform radius.

Basketweave Configuration

The original multiple capstan concept used a "basketweave" configuration, so a test of this configuration was undertaken. The design of the multiple capstan test section allowed reversible conversion to a basketweave configuration with minimal effort. Results of tests of this configuration on the manikin are shown in Figure 23.

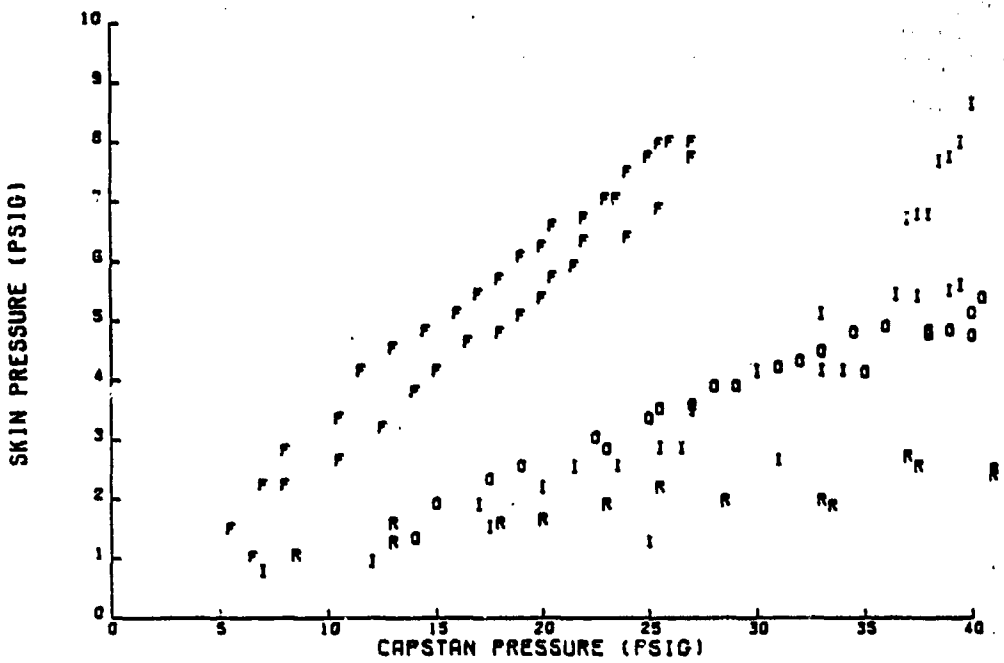


Figure 23. Manikin skin pressure under a multiple capstan section in a basketweave configuration.

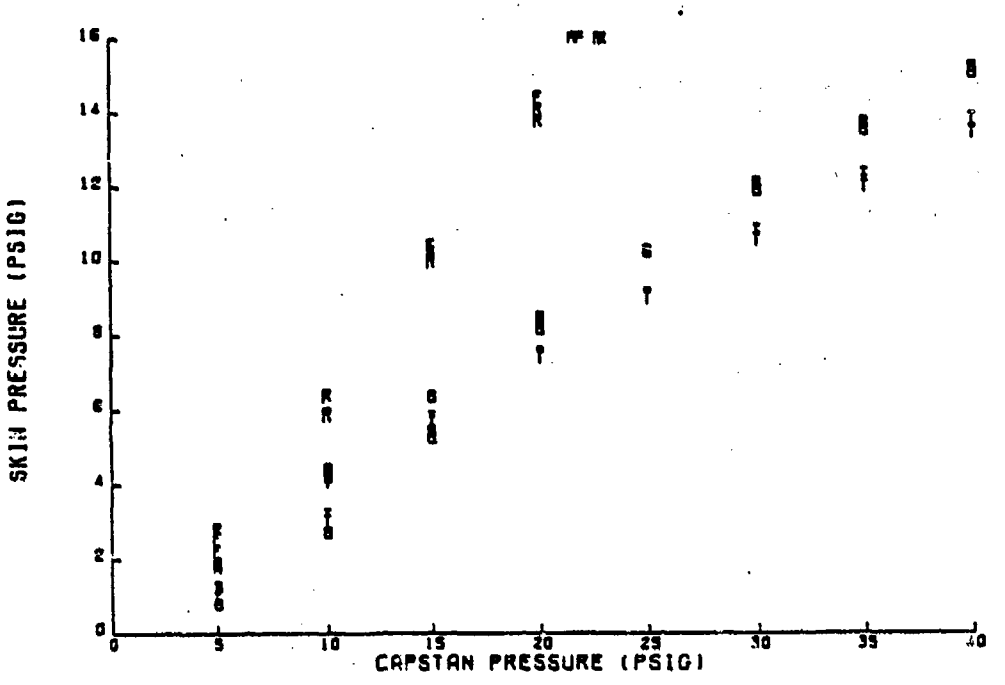
Comparison of test results between the basketweave and low-pressure capstan design was inhibited by an inherent configuration difference. The basketweave configuration deforms individual capstan tubes into an oval shape, while other capstan configurations yield cylinders. No effective technique was available to measure the effective radius of the basketweave capstans. As a result, no empirical measure of the theoretical skin pressure (i.e., capstan to limb ratio) in a basketweave test is available. Assuming a cylindrical set of capstans, of the same size used for multiple capstan tests (same equipment used for both tests), the theoretical capstan to skin pressure ratio was 5.82:1. Obviously, the skin pressure measured at the front of the manikin thigh exceeds this value by some 70%. This higher skin pressure is especially surprising when the frictional losses observed in the low-pressure capstan tests are considered.

Careful inspection of the test section during the tests revealed an explanation for the higher skin pressures. The test section was fitted tightly around the manikin and even at full inflation pressure, the capstans were significantly

flattened by the interdigitized tapes. As a result, the capstan cross-section appeared more like ellipses than circles; thus, the effective radius of each capstan bearing on the interdigitized tapes is significantly lengthened.

Comparison of Multi-Capstan Configurations

A separate experiment was undertaken to compare the basketweave and multiple capstan configurations, while minimizing effects of local topography. In this experiment, the test section was placed over a cylindrical base and a 500-ml Travenol bag filled with approximately 100 ml water was used to measure pressure under the suit. The objective of this test was to measure normalized pressure over a large area. Skin pressures were consistently higher at all capstan pressures for the multiple (low-pressure) capstan configuration than for the basketweave configuration (Fig. 24).



F = Front or top (under capstans) of low-pressure capstan
R = Rear or bottom (opposite capstans) of low-pressure capstan
T = Top or front (under capstans) of basketweave
B = Bottom or rear (opposite capstans) of basketweave

Figure 24. Skin pressure comparison of low-pressure capstan and basketweave multi capstans.

Multiple Capstan UP Suit Design

A review of the anthropometry of present centrifuge subject panel members revealed that the most commonly used G-suit sizes were medium-regular and

small-long (in approximately equal numbers). The subcontractor (ILC Space Systems) for this effort was therefore instructed to build one medium-regular and one small-long multiple capstan UP suit. Figure 25 shows a portion of an ILC drawing of the proposed design.

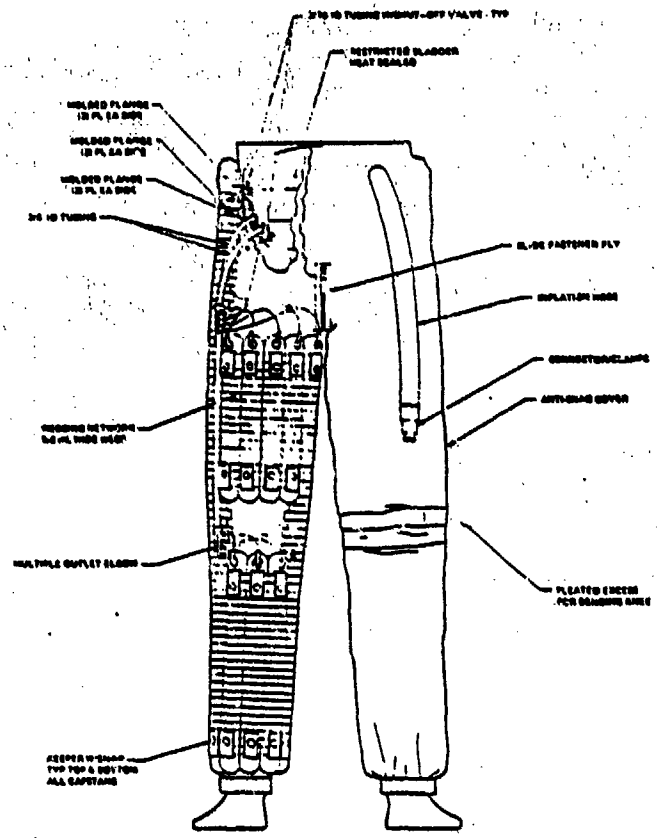


Figure 25. Multiple capstan uniform pressure anti-G suit.

A sample set of calculations was developed for the medium-regular suit and ILC was instructed to use similar calculations in all cases. The basic principle of the calculations was that the suit would be continuously adjustable for limb-to-capstan pressure ratio, for any number of capstans between two and six (or two and five for the calf). The same range of ratios should be available for top and bottom of calf and thigh.

Limb-to-Capstan Pressure Ratio was calculated by the relationship:

$$R = \frac{P_l}{P_c} = \frac{ND_c}{D_l}$$

where

D_c = Diameter of capstan
D_l = Diameter of limb
N = Number of capstans
P_c = Pressure in capstan
P_l = Pressure in limb
R = Pressure ratio = $P_l : P_c$.

Data in Table 3 were developed, using this relationship. These data show that for a maximum limb diameter of 20.22 cm (7.96 in.) and a minimum diameter of 17.37 cm (6.84 in.), corresponding to a maximum upper thigh circumference of 63.5 cm (25 in.) and a minimum circumference of 54.61 cm (21.5 in.) for a medium-regular suit size, continuous adjustment could be achieved with a capstan diameter adjustment range from 2.79 cm (1.1 in.) to 4.45 cm (1.75 in.) (Table 3). This capstan diameter adjustment range should have produced a pressure ratio adjustment range from 0.35 to 1.3, which should have been sufficient for test purposes. This range also established a requirement for approximately 5.08 cm (2 in.) of suit circumference adjustment to accommodate the capstan diameter changes over and above the 8.89 cm (3.5 in.) circumference adjustment required for the medium-regular size variation. A capstan adjustment range of 2.79 cm (1.1 in.) to 4.45 cm (1.75 in.) was calculated to provide the actual pressure ratio ranges shown in Table 4.

Multiple Capstan Suit Testing

Initial plans were to conduct multiple capstan suit runs with a variety of capstan pressure to skin pressure ratios to determine the ratio which afforded the greatest $+G_z$ tolerance/endurance. We discovered early in the testing program, however, that calculated capstan to skin pressure ratios could not be achieved; with the capstans set for a 1:1 pressure transfer only a 4:1 pressure transfer was actually attained.

A single capstan anti-G concept has been extensively assessed in the past. Most studies pointed out advantages of this concept over standard anti-G suits in regard to comfort and/or $+G_z$ protection. The studies also pointed out severe operational deficiencies, such as the requirement for two pressure sources, one for the capstan and one for the abdominal bladder.

The multiple capstan approach would eliminate one of the more profound problems of the single capstan design: the need for two pressure sources. In an effort to determine once and for all whether the multiple capstan approach could be used for an operational anti-G suit, we attempted to attain the greatest possible pressure transfer from the capstans to the subject's skin. A total of 32 centrifuge runs were conducted. Twenty-seven runs were conducted

TABLE 3. PRESSURE RATIO AND CAPSTAN DIAMETER CALCULATED FOR CONTINUOUS ADJUSTMENT OF MULTIPLE CAPSTAN UP SUIT*

Values are $\frac{P_l : P_c}{D_{c(in)}}$

Number of capstans									
6		5		4		3		2	
max	min	max	min	max	min	max	min	max	min
Maximum thigh diameter (D_l) = 20.22 cm (7.96 in.) (Circumference = 63.5 cm (25 in.))									
1.32 / 1.75	1.10 / 1.46	1.10 / 1.75	.88 / 1.4	.88 / 1.75	.66 / 1.31	.66 / 1.75	.44 / 1.17	.44 / 1.75	.28 / 1.1
Minimum thigh diameter (D_l) = 17.37 cm (6.84 in.) (Circumference = 54.61 cm (21.5 in.))									
1.53 / 1.75	1.28 / 1.46	1.28 / 1.75	1.02 / 1.4	1.02 / 1.75	.77 / 1.32	.77 / 1.75	.51 / 1.16	.51 / 1.75	.32 / 1.1

$R = \frac{P_l}{P_c} = \frac{ND_c}{D_l}$

P_l = Pressure in limb (thigh)

P_c = Pressure in capstan

N = Number of capstans

D_c = Diameter of capstan

D_l = Diameter of limb

* Medium-regular suit size assumed.

TABLE 4. PRESSURE RATIO (R) RANGES PRODUCED BY ADJUSTMENT OF CAPSTAN DIAMETER FOR MULTIPLE CAPSTAN UP SUIT*

Number of capstans									
6		5		4		3		2	
max	min	max	min	max	min	max	min	max	min
Maximum thigh diameter (D_1) = 20.22 cm (7.96 in.) (Circumference = 63.5 cm (25 in.))									
.32	.83	1.10	.69	.88	.55	.66	.41	.44	.28
Minimum thigh diameter (D_1) = 17.37 cm (6.84 in.) (Circumference = 54.61 cm (21.5 in.))									
1.53	.96	1.28	.80	1.02	.64	.77	.48	.51	.32

$$R = \frac{P_l}{P_c} = \frac{ND_c}{D_l}$$

P_l = Pressure in limb (thigh)

P_c = Pressure in capstan

N = Number of capstans

D_c = Diameter of capstan

D_l = Diameter of limb

* Medium-regular suit size assumed.

with subjects wearing the standard CSU-13B/P suit, and 5 runs with the multiple capstan suit. Skin pressure data were collected on 15 runs. The runs with the standard anti-G suit were conducted to establish and maintain a reliable $+G_z$ simulated air combat maneuver endurance level among our subjects.

Problems were encountered with suit fit and an inefficient webbing system. The best approach to overcoming these problems appeared to be custom-fitting of the suit and a new webbing system which minimized friction between tapes and entanglement. To this end, Technology Incorporated made the following recommendations:

1. Have ILC optimize design of the webbing network, fit during seated posture, and size and placement of abdominal bladder;

2. Have three subjects custom-fitted in the optimized suit;

3. Gather $+G_z$ tolerance and endurance data on the 3 custom-fitted subjects for comparison with the standard anti-G suit using the same centrifuge profile currently in use. If the USAFSAM centrifuge was being modified, use an alternate centrifuge facility; and

4. Continue centrifuge runs for the 5 subjects presently on the study to ensure that a reliable baseline endurance was established and maintained; and to measure the maximum $+G_z$ endurance that could be achieved with the present suit fitted for maximal pressure transfer.

Mean G-tolerance times for 3 subjects riding the 4.5 to +7 G_z profile-to-fatigue indicated that optimally fitted, the multiple capstan suit increased G-time tolerance approximately 60% over the standard suit. Six subjects rode the centrifuge in support of the multiple capstan protocol; however, because of repeated suit failures only 3 subjects underwent rides wearing the multiple capstan suit. One subject had a run of 880 s duration wearing the multiple capstan suit, and another had a run of 784 s duration. In both instances, G-time tolerances were over 100% greater than those achieved from their best rides in the standard cutaway suit.

Because of the significant loss in applied pressure during transfer from capstans to skin, a subcontract was awarded to ILC Space Systems, Houston, Texas, to determine the cause of this pressure loss and to design a webbing network for maximal pressure transfer. The resulting report concluded that: the mockup which Technology Incorporated had submitted was more efficient than the prototype multiple capstan suit. Efficiencies in excess of 70% could be obtained.

Leg clearances were measured in the F-16 and F-15 cockpit mockups at USAFSAM to determine the availability of room inside the foot wells for the use of capstans on legs of the anti-G suit. This evaluation was done with a 60th percentile subject. The evaluation suggested that only .64 cm (.25 in.) of room was available on either side of the leg in the F-16 cockpit in the absence of the suit, resulting in only 20.32 cm (8 in.) available for application of the capstan concept across the top of the thigh. In the F-15 cockpit, this was

increased to approximately 33.02 cm (13 in.) due to the increased leg room of 3.493 cm (1.375 in.) on either side of the leg.

In an attempt to ascertain the feasibility of the multiple capstan concept within present and future airframes, we constructed a matrix with existing data on availability of space and input/output pressure ratios with the capstan concept (Table 3). This matrix included the number and size of capstans that were feasible within this environment. The calculations were based on two assumptions. First, the only space available for capstans in the present aircraft is 20.32 cm (8 in.) on top of the thigh. Second, the relationship between the number or size of capstans and friction was not included. The exclusion of the friction term is possible since friction would only decrease the feasibility of the concept beyond that which would be obtained in the ideal situation. Therefore, if the suit was to be determined as not feasible, then the real situation would be even less feasible in the aircraft.

Reticulated Foam Anti-G Suit

The problems of weight, bulk, and sizing of the multiple capstan suit contributed to a lack of acceptance of this suit design. Technology Incorporated turned to an alternate UPS design concept, reticulated foam, as an approach to further research and development of lower body uniform pressurization.

Reticulated foam retains its shape regardless of the pressurization level, thus forming a progressively more rigid "cylinder" as the $+G_z$ level is increased and more counterpressure is applied to balance the increasing hydrostatic load. This suggests that as long as the cockpit accommodates the pilot initially, it would also accommodate his anti-G suit under full pressurization. This suit appeared to offer structural stability under loading, has a low pressurization volume, hence is easily inflated, and initially exhibits an extremely high pressure-transfer ratio. The suit consists of an open-celled polyester foam surrounded by a urethane-coated nylon bladder type material. When this material was bonded together and wrapped around the leg, it transmitted a minimum of 80% of the input pressure directly to the leg. This foam has withstood forces well beyond those expected to be encountered in the aircraft. These facts, coupled to the low-pressurization volume and sizing ease, made the reticulated foam suit an attractive alternative to the multiple capstan approach.

A subcontract was let to ILC Space Systems to study materials, adhesives, and bonding techniques and to provide a preliminary design for a reticulated foam anti-G suit.

Anti-G suit thigh sections were also designed and fabricated as a part of this ILC effort. The foam selected and built into the thigh sections demonstrated that it could withstand internal pressures of greater than 28 psi without forming aneurysms (weakened areas) in the foam. Thigh sections were subsequently evaluated by Technology Incorporated on a manikin leg using our skin pressure measuring system to record pressure transferred from the suit to the surface of the manikin. Pressures measured on the manikin thigh averaged approximately 80% of those measured in the reticulated foam thigh section. Skin pressures equal to those in the reticulated foam thigh section were recorded in many areas. Points showing the least pressure transfer were under the creases formed when the section was wrapped around the thigh, and under indentations in

the hard polyurethane covering. By comparison, only a 25% pressure transfer efficiency was achieved with the multiple capstan suit.

Development of the reticulated foam anti-G suit was divided into two phases with fabrication (Phase I) subcontracted to ILC Dover. Phase I ended with the delivery of 3 thigh sections which showed promise for future development. The thigh sections were tested by Technology Incorporated for applied pressure, fill time, and material integrity. Phase II consisted of fabrication, test, and evaluation of complete anti-G suits made from reticulated foam. Covering materials were a urethane-coated Kevlar for the outer restraint layer. Suits were constructed to be worn under a flight suit and sized to fit the 5th to the 95th percentile in the medium-regular size range.

Configuration of each suit was modular. Suits differed in the thigh and calf sections in that one was of 1.27-cm (0.5-in.), 80 psi foam bonded to both inner and outer layers. The double-sided bonding of this suit limited inward expansion of the suit and encased the legs in a rigid cylinder.

The second suit was manufactured with a 0.64-cm (0.25-in.) foam bonded to the outer layer only. This suit transferred to the skin, as a minimum, the pressure supplied by the anti-G valve (i.e., a 1:1 ratio).

Abdominal bladders provided with the suits also differ as to construction and operation. One bladder was configured similar to the bladder used in the present CSU-13B/P anti-G suit, which presses into the abdomen. The second abdominal bladder had reticulated foam bonded to both outer and inner covers and thus allowed only limited inward travel of the bladder, presenting the wearer with a rigid platform with which to strain against. The abdominal bladders were interchangeable so that each configuration of thigh/calf module could be tested with each type of abdominal bladder. One additional suit was to be manufactured during this effort which incorporated the best features of each concept.

Manikin testing of both the "bladder" and "cylinder" G-suits was conducted concomitantly with the human centrifuge testing. Inflation rates were measured for both the reticulated foam (REF) suits and the standard five-bladder suit (CSU-13B/P). Rates of inflation (psig s^{-1}) to 5 psig of the 3 suits were compared, and are shown in Table 5.

In verification of the slow filling time for the REFB, both subjects who have worn the suit during human centrifuge runs have complained that the abdominal bladder was still filling after they had reached a high +G plateau. The cause of this slow filling time is probably a combination of the small inside diameter, 0.64 cm (0.25 in.), of the tubes supplying the bladders and the larger volume of the REFB suit, compared to the standard CSU-13B/P suit.

Manikin tests with the REFC suit, which incorporated the platform-design abdominal bladder in its initial configuration, revealed that this bladder failed at the heat-sealed rib under static tests to 5 psig. The 1.27-cm (0.5 in.) foam thigh/calf bladders and platform design abdominal bladder had been fitted to the manikin and fill times to 5 psig were being recorded when failure occurred.

We notified ILC, Dover and a new abdominal bladder was fabricated. The thigh/calf bladders of 1.27-cm (0.5 in.) foam bonded to both sides were also

TABLE 5. ANTI-G SUIT RATE OF INFLATION
(psig s^{-1})

Suit	Bladder		
	Abdominal	Thigh	Calf
REF cylinder (REFC)	9.5	10.0	10.5
CSU-13B/P	11.0	11.0	11.0
REF bladder (REFB)	14.0	14.5	14.0

returned for sizing adjustment, required to optimally fit the suit to an experienced test subject. A close-fitting suit was mandatory if the full anti-G benefit were to be attained.

Two subjects wore the REFB suit during runs on the human centrifuge. Both subjects complained of pain around the knees. Pain was accompanied by considerable petechiation in one of the subjects.

Subjects complained of discomfort induced by the large size of the REFB abdominal bladder. We, therefore, had the subjects trace the area of the abdomen they wanted the bladder to cover; the areas traced were in close agreement with one another. Since one of these subjects was probably the most experienced high-G rider on the centrifuge panel, these recommendations were considered worthy for incorporation into future designs.

Final determination of the optimal configuration of a bladder was not made because of: (1) lack of available centrifuge time due to higher priorities such as Tactical Air Command (TAC) training and Technical Library Services Section (TLSS) evaluation, and (2) lack of trained subjects to fit the suits.

A brief summary of findings from work with both the multiple capstan and reticulated foam anti-G suits is included as Appendix A. This paper entitled "Current Research and Development of Anti-G Suits" was co-authored by Drs. Krutz and Darrah. This paper was also presented at the 1983 SAFE Symposium in San Antonio, Texas, and subsequently published in Hazard Prevention (May/June 1985).

DISCUSSION

Task 2 - Uniform Pressure Anti-G Suit

Several important points were observed with respect to this anti-G suit concept. First, the multiple capstan produced almost twice the skin pressure produced by the basketweave configuration design. Second, the front and rear (top and bottom) pressure tracked closely, implying that the majority of pressure losses occurred in the capstan/interdigitized tape sections, rather than along the skin surface. Third, the response was linear and repeatable, implying that the nonlinearity and scattering seen in other experiments is due to local topology and edge effects rather than inherent flaws in the system.

The multiple capstan configuration had the same inherent comfort disadvantage as the standard capstan. The amount of "slack" allowable around a limb was even reduced (i.e., the smaller capstan circumference provides less slack when inflated). This slack might be significantly relieved by changing from 6 capstans to 3 or 4, but at the expense of increased interference in the cockpit, since their diameter would be proportionally increased.

The multiple capstan also has an inherently increased resistance to limb diameter enlargement. Resistance to enlargement comes from friction between interdigitized tapes, and resilience in the capstan bladder opposing reduction in capstan size (i.e., to allow enlargement of limb volume). Resistance is multiplied in the multiple capstan approach due to the identical mechanics which multiply the force applied to the limb.

The multiple capstan approach had an excellent potential for gradient pressure application. That gradient may be locally and regionally controlled. For example, using 6 tubes, 1 tube might run the entire length from waist-to-ankle similar to the conventional capstan. A second tube would run the length from groin-to-ankle along the upper interior gradient of the leg. Four other bladders would be spread between these two, around both upper- and lower-leg sections.

The second effort, just mentioned, was to elucidate which features of the modified capstan suit set it apart from the CSU-13 B/P. Among those distinctive features, we hoped to find an explanation of its improved performance. The following observations appear to be significant.

First, capstan suits apply pressure over the maximum possible surface areas. From an engineering point of view, this is an efficient and desirable way to accomplish the physiological goals of G-protection. Efficiency is defined here in terms of the magnitude of skin pressure per square inch which is required to accomplish a given increase in peripheral resistance of the vascular tree.

This observation points to the second distinctive feature of the modified capstan suit: the remarkably low skin pressures observed. Actual skin pressures measured under the modified capstan suit are generally less than 30% of what we would predict from radius effects and comparably less than those measured beneath the CSU-13 B/P for a given G-situation. This phenomenon must surely contribute to G-endurance during air combat maneuver (ACM) profiles. The amount of distress that a test subject must endure would be predictably less if

a given amount of vascular compression can be accomplished with significantly less applied force per square inch.

The third noteworthy feature of the modified capstan suit was the design of the abdominal bladder. Specifically, the abdominal bladder was built in such a manner as to restrict its ultimate growth. Anyone who has worn a CSU-13 B/P G-suit inflated to 8 psi will testify to the amount of effort required to counteract the sensation of being squeezed into two pieces at the abdomen. Rather than augment the M-1 straining maneuver, we surmised the stress imposed upon the subject at these pressures may, in fact, impair his straining.

Multiple Capstan Suit Evaluation

There were several probable reasons for the lower than expected pressure transfer encountered in testing the Multiple Capstan suit. Suit fit unquestionably played an important role; i.e., to most efficiently apply pressure to the skin using the capstan concept, the suit must be tight fitting. Ideally, the suit should be custom fitted for each individual. The 5 subjects in this study required a medium-regular suit according to data furnished in the 1979 AMRL anthropometric study (1). The one suit available was extremely difficult to individually size, requiring several hours per subject; and even then, a completely correct fit was not attained.

Some of the problems with suit fitting were due to the wide range of subject sizes covered in the six-size tariff proposal for anti-G suits. Unfortunately, the multiple capstan anti-G suit is, in reality, not an anti-G suit, but rather a partial pressure suit. From pressure transfer considerations, a better fit could probably be achieved with the twelve-size tariff. Furthermore, if the suit had been constructed like a partial pressure suit (with excess fabric in the seat), the problem experienced with the suit riding up in front and down in back when the subject was seated, could have been prevented. There was not enough take-up in the laces controlling capstan diameter size when the suit was comfortably fitted to the subjects. Conceivably, there were subjects in the medium-regular size range whom the suit would have optimally fit; however, we did not find them among the subjects available to us.

Another area of the multiple capstan suit which definitely had a negative effect on pressure transfer was the webbing network. There was excess friction between the interdigitized tapes and probably entanglement of the tapes under the capstans.

It was difficult to correlate the increased G-time tolerance attained from wearing the multiple capstan suit with any measured parameter. Certainly the skin pressures were much less and there did not appear to be a significant difference in the uniformity of circumferential pressure application between the capstan and standard anti-G suit. Nevertheless, the significant increases in G-time tolerance achieved in the Shaffstall-Burton study (4) and the increases in G-level tolerance reported in previous studies with "uniform pressure" concepts are valid data and the mechanism for the observed increases should be explored.

One obvious reason for the apparent superiority of the multiple capstan suit is the application of counterpressure to a larger area of the legs. This

uniform pressure would prevent the pooling of blood in areas which are not counterpressurized by the standard anti-G suit.

Analysis suggested that even with the ideal conditions for performance and fit of the anti-G suit, a 25% pressure transfer ratio would be obtained. Therefore, it appeared that the multiple capstan concept was not the most physically effective way to apply uniform pressure to the body. We found no solid engineering approach for increasing this transfer ratio. Furthermore, the problems of weight, bulk, sizing, and fitting would still have to be solved before the suit would be an acceptable item of life-support equipment.

The multiple capstan research reported here reaffirmed previous findings that uniform pressure over the lower body yields greater $+G_z$ endurance time than the same amount of bladder pressure in the standard five-bladder suit. It is significant that the increased $+G_z$ endurance times were achieved with only a fraction of the applied skin pressure, and at approximately the same heart rates.

Reticulated Foam Anti-G Suits

Although no firm conclusions can be drawn, two situations are apparent which will impact future reticulated foam anti-G suit designs:

1. Significant diaphragm support is required from the G-suit, even for highly trained subjects, in order to "get on top" when undergoing simulated air combat maneuvers (SACMs) in the centrifuge. This indicates that the optimal abdominal bladder configuration lies somewhere between a "platform" bladder and the enlarged standard design bladder (i.e., perhaps the standard anti-G suit abdominal bladder).

2. The pressure exerted by the thigh and calf bladders of the "bladder" reticulated-foam, uniform pressure modules produces petechiae and pain during $+G_z$ exposure in unpressurized areas (e.g., behind knees).

It is essential that studies be conducted to determine an optimal abdominal bladder design since the protection afforded by this component of the anti-G suit is most essential during rapid-onset accelerations. The bladder must help to maintain heart-eye distance during $+G_z$ onset and not contribute to fatigue during sustained $+G_z$ by causing pain from too much abdominal compression.

Optimal leg pressurization requires further investigation; although high pressures appear desirable during G-onset, the discomfort produced in unpressurized areas may contribute to fatigue during prolonged G exposure.

CONCLUSIONS

For the last four decades, numerous attempts have been made to improve on the increased G-tolerance afforded by the standard cutaway five-bladder anti-G suit. The results of this research have indicated that G-tolerance, which is defined as the maximum G-level which can be attained, is indeed separate from G-endurance, or sustained performance at a given G-level(s) once attained. To

attain a higher level, the extreme importance of the abdominal bladder has been demonstrated. Also the relatively greater importance of leg counterpressure (albeit a low pressure), once the G-level was reached and sustained performance is desired, was demonstrated.

Comparison of the multiple capstan suit with the standard CSU-13 B/P design was undertaken in an effort to better understand reasons for the superior performance of the capstan suit when G-endurance is considered. Capstan suits apply pressure over the maximum possible surface areas, resulting in improved efficiency in magnitude of skin pressure per square inch needed to accomplish a given increase in peripheral resistance of the vascular tree. For a given amount of vascular compression realized, capstan suits produce significantly lower skin pressures per unit of surface area than does the CSU-13 B/P suit. This phenomenon may contribute to increased G-endurance during ACM profiles. We initially thought that the abdominal bladder design of the modified capstan suit offered advantages over that of the CSU-13 B/P suit; the bladder was built in such a manner as to restrict its ultimate growth reducing the sensation of being excessively squeezed in the abdominal region. This idea proved not to be the case and the necessity of diaphragm support during high-onset rate G was demonstrated.

Problems encountered with the multiple capstan suit involved difficulties in fitting a one-size suit to various individual subjects. The one suit available was extrememly difficult to individually size, requiring several hours per subject; and even then a completely correct fit could not be attained. (Ideally, anti-G suits should be custom fitted for each individual.) These problems resulted in lower-than-expected pressure transfers observed in testing the suit. Another area which also contributed to reduction of pressure transfer was the webbing network; there was excess friction between interdigitized tapes, and probably entanglement of tapes under the capstans.

Even with ideal conditions for performance and fit of the multiple capstan anti-G suit, a 25% pressure transfer ratio would be obtained. It, therefore, appeared that the multiple capstan concept was not the most effective way to apply uniform pressure to the body. Furthermore, problems of weight, bulk, sizing, and fitting would still have to be solved before the suit would be an acceptable item of life-support equipment.

Studies of the reticulated foam anti-G suit outlined several areas requiring further development before this type of suit can be fully evaluated. First, significant diaphragm support is presently required, even for highly trained subjects. This concept indicates that the optimal abdominal bladder configuration lies somewhere between a "platform" bladder and the enlarged standard design bladder (i.e., perhaps the standard anti-G suit abdominal bladder). This UPS concept provides uniform pressure in a suit which does not expand to any appreciable degree during inflation to high pressure, and therefore is compatible with the limited space in the F-16 between the center console and leg restraints. This fact argues well for its continued development.

Finally, it is paramount to point out that an inordinate amount of time was consumed when anti-G suit modifications were dictated as a result of human centrifuge evaluations. Several months were lost during each modification since there are no known builders of life-support equipment in this country with dedicated R&D facilities. Normal production-line equipment fabrication had to

be interrupted to meet our needs, during which time the size requirements changed for our human centrifuge volunteer subject panel. New subjects had to be selected and trained during a time-consuming process.

These studies have once again confirmed the urgent need for an in-house facility at USAFSAM to both fabricate and modify prototype life-support equipment. An outline for such a facility is included as Appendix B.

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APPENDIX A

CURRENT RESEARCH AND DEVELOPMENT OF ANTI-G SUITS

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ABSTRACT

The $+G_z$ loads which modern fighter aircraft generate are rapidly approaching man's tolerance limits. Efforts being made in the R&D community to combat these ever-increasing G-loads include new and improved anti-G suits. This paper discusses such an effort using lower body uniform pressure to support the cardiovascular system during the high $+G_z$ stress. Two concepts were examined viz., multiple capstans to uniformly tighten the G-suit fabric around the leg and reticulated foam to evenly transfer pressure from the suit to the skin.

The prototype multiple capstan suit was tested and evaluated on the United States Air Force School of Aerospace Medicine (USAFSAM) human centrifuge. $+G_z$ tolerance/endurance limits were measured in subjects wearing the multiple capstan suit and compared to those achieved with the standard CSU-13B/P anti-G suit. Bulk and ease of donning were assessed as well as compatibility with the F-15 and F-16 cockpits.

An open-celled reticulated foam was the basis for the other uniform pressure anti-G suit concept. The foam provides uniform pressure distribution with minimal suit expansion during pressurization. Prototype reticulated foam anti-G suit thigh sections have been assessed and preliminary results indicate that high skin pressure transfer ratios are attained.

INTRODUCTION

The $+G_z$ protection afforded by the standard anti-G garment/valve was adequate up to the advent of the F-15, F-16, and F-18. These aircraft have ushered in a new high-G environment in which man's tolerance limit is being severely tested. This has dictated an intensive effort to increase tolerance limits. A major part of this endeavor is to determine if a new anti-G suit can be developed which will offer a significant increase in $+G_z$ tolerance/endurance compatible with pilot acceptance.

Since the early 1940's, anti-G garments have been used to augment straining maneuvers in providing protection against $+G_z$ induced blackout. One of the earliest garments employed the use of water to counterbalance G-induced increases in hydrostatic pressure. A variety of approaches using pneumatic bladders were tried in an attempt to provide a gradient pressure which appeared to be the best physiological approach. This concept was essentially abandoned after studies on the Mayo Clinic centrifuge (1) found that a single pressure garment with five interconnected pneumatic bladders provided equivalent protection. Although the 5-bladder configuration has undergone many alterations over the years (i.e., it has been made to be over and under the flying coveralls, and incorporated into the flying coveralls), the basic concept has remained unchanged for four decades and continues to be the anti-G suit preferred by pilots.

The most promising anti-G suit concept to evolve since the 5-bladder configuration has been uniform lower body pressurization (2,3). This concept may offer significant increases in protection by incorporating uniform longitudinal and circumferential pressurization to dependent areas of the body rather than the same pressure applied to scattered areas, e.g., the standard anti-G suit. Presumably, uniform pressurization lessens the degree of blood pooling as seen with the standard 5-bladder suit under high sustained $+G_z$. Attempts to utilize this concept have included a modified CSU-4/P suit (2) and, more recently, a modified capstan suit (3). While each of these concepts has produced increases in $+G_z$ tolerance and/or endurance, development has not been pursued because of significant engineering incompatabilities.

Two recent approaches to a uniform pressure anti-G garment have been the multiple capstan suit to uniformly tighten the suit fabric around the leg and reticulated foam to evenly transfer pressure from the suit to the skin.

MULTIPLE CAPSTAN SUIT

The multiple capstan suit was an attempt to circumvent a significant engineering problem encountered by Shaffstall and Burton (3) in the development of a modified capstan suit. Although they found a significant increase in $+G_z$ endurance, viz. 133%, during simulated air combat maneuvers (SACM), the need for two pressure sources, one for the abdominal bladder and one for the capstans, precluded further development. Thus, one of the primary concerns in the development of the multiple capstan suit was establishing a single pressure source. This was achieved by utilizing six capstans for the calf. Calculations suggested that if the summation of individual diameters resulted in a diameter equal to that of the thigh, a 1:1 pressure transfer from the suit to the thighs would be achieved. However, resultant skin pressures as measured by pneumatic switches were 25% of that recorded in the capstans. This inefficiency was attributed to several factors including friction between the tapes, friction between the suit materials and skin, and tape entanglement.

In an attempt to achieve the greatest possible skin pressure transfer ratio, prior to the run, the suit was tightened to the comfort limit and the capstans were allowed to expand maximally without reaching maximal diameter at peak capstan pressures (8 psi). This resulted in a pressure transfer efficiency of approximately 50%. A limited number of "best fit" suit runs using the SACM profile on the USAFSAM human centrifuge demonstrated $+G_z$ endurances similar to those achieved by Shaffstall and Burton using the modified capstan suit (3). These data appear to indicate that the multiple capstan suit, if optimally fitted, provides substantial increases in $+G_z$ endurance when compared to the standard anti-G suit. However, weight, thermal load,

sizing, and fitting problems are significant detriments to further development.

RETICULATED FOAM

An open-celled reticulated foam has been developed as an alternate uniform pressure anti-G suit concept concomitantly with the multiple capstan suit. This foam provides uniform pressure distribution with minimal suit expansion during pressurization and essentially forms a "steel cylinder" to encase the thighs and calves, thereby preventing blood pooling during exposure to $+G_z$ acceleration. The only factor presently limiting foam thickness is the adhesive used to secure the foam to the inner and outer layers of the suit and the foam porosity. Suit thickness should permit use of the foam anti-G suit in even the most space-limited cockpits, e.g., the F-16. Prototype reticulated foam anti-G suit thigh sections have been assessed and preliminary results indicate increased pressure transfer efficiencies, i.e. approximately 80% of the suit pressure is transferred to the skin as opposed to 25-50% in the multiple capstan suit.

CONCLUSION

Uniform lower body pressurization appears to offer the most promise for improving $+G_z$ tolerance. Multiple capstans and reticulated foam are the two most recent approaches to solving the engineering incompatibilities seen in previous attempts to develop this concept for use in fighter-type aircraft. Significant weight, bulk, sizing, and pressure transfer problems inherent in the multiple capstan argue against further development. Reticulated foam may offer a significant breakthrough in G-suit technology as a possible method for uniform pressurization without many of the problems encountered with other concepts.

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FOOTNOTE: The volurtary informed consent of all subjects was obtained in accordance with AFR 169-3.

ABOUT THE AUTHOR

Dr. Robert W. Krutz, Jr., is a Research Physiologist for Technology Incorporated, Life Sciences Division, in San Antonio, Texas. He is currently responsible for the research and development of anti-G suits for the U.S. Air Force at the School of Aerospace Medicine, Brooks AFB, Texas. He received his B.S. degree (Pharmacy) from the University of Mississippi and his M.S. and Ph.D. degrees (Physiology) from the University of Southern California.

Dr. Krutz has over 20 years of experience in military life support equipment design, development and operational testing. Specifically his military research has included $+G_z$ protective methods, oxygen breathing systems and chemical defense equipment. Dr. Krutz is an Associate Fellow of the Aerospace Medical Association.

Dr. Mark I. Darrah is employed as a biomedical Engineer with the Life Sciences Division of Technology Incorporated in San Antonio, Texas. He is presently under contract to the Aerospace Research Branch of the School of Medicine at Brooks AFB, Texas, to study the effects of head/neck loading in the high $+G_z$ environment of today's high performance aircraft.

Dr. Darrah received a B.S. degree (1975) in Biology from Delaware Valley College in Pennsylvania and his M.S. (1979) and Ph.D. (1982) degrees in Biomedical Engineering from Iowa State University. His research has been centered on cardiovascular dynamics and muscular contractility in the exercise environment. Dr. Darrah is a member of IEEE and the Aerospace Medical Association (LSBEB). ●

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APPENDIX B

PROPOSED IN-HOUSE LABORATORY FACILITY FOR PRODUCTION AND MODIFICATION OF RDT&E PRE-PROTOTYPE MODELS OF AIRCREW LIFE-SUPPORT EQUIPMENT

INTRODUCTION

The complexity of current aircrew life-support equipment, or personal protective equipment (PPE), and the many factors which have to be considered during design of such equipment, dictate extensive and progressive RDT&E phases during which detailed design criteria are established and evaluated. A major problem in design and development of this equipment is achievement of an optimum balance between equipment performance and its subjective acceptability when integrated into the cockpit, cabin, or mission environment. Progress toward this optimum balance depends upon incorporation of continuing feedback from human subjects testing the equipment and from USAF personnel evaluating test results and design modification options for incorporation of the feedback.

Requirement specifications for items of aircrew PPE rarely, if ever, specify in detail the means by which the many important and often conflicting requirements shall be met. Even where there is a full understanding and appreciation of all requirements by the selected development contractor, past experience has indicated the inevitable need for a progression of preprototype models of equipment, each of which has to be fully evaluated to provide guidance for further developmental progression. In many instances, the modifications required to effect the desired changes are of a relatively minor nature, provided that the necessary support production facilities and appropriate expertise are available.

Currently, provision of such facilities and expertise rests primarily with the contractor. Drawbacks to this arrangement include serious limitations with respect to onsite working space and basic laboratory facilities available, and the fact that contractor personnel assigned to this task must be selected on the basis of other expertise and must devote full time to defined project tasks.

Productivity rates, production costs, and quality control of items produced could be enhanced if in-house laboratory facilities and a minimal number of trained personnel were available to fabricate pre-prototype models of PPE for RDT&E. Another major advantage of such an in-house facility would be reduction of dead times occurring between evaluation, redesign, incorporation of design changes, and reevaluation. Overall, greater economies in RDT&E time and costs of PPE items would be realized.

The proposed in-house laboratory facilities would provide capabilities of:

a) Rapidly effecting modifications to contractor's developmental equipment where such equipment falls short of specific test standard requirements. In-house modified PPE items would serve as models for industry to process development.

b) Exploring ideas to establish important design criteria before involvement by industry.

c) Producing laboratory prototype equipment to serve as models for industrial production.

d) Exploring sizing requirements for PPE items to develop commercial production specifications.

In the longer term, the proposed facility would provide a pool of in-house expertise in detailed design and fabrication of aircrew PPE. Such expertise would enhance significantly the extent of detailed design guidance available to industry.

Typical tasks which could be undertaken in the proposed in-house facility include:

a) Construction of, or modification to, all forms of pressurized bladder and pressure holding garments. Examples are G-protective garments, full and partial pressure suits, and jerkins or waistcoats. Typical work on G-protective garments might be: exploration of means of providing full lower torso and limb coverage incorporating mobility features at knee joints and possibly at waist, groin, and thigh joints; exploration of basic sizing criteria and means of restricting pressurized bulk and "as-worn" pressurized volume; exploration of means of providing rapid adjustment of torso and limb girth of anti-G suits to allow for seasonal or operational changes of aircrew protective clothing such as chemical defense undergarments; and investigation of "low-friction" lacing systems to facilitate constant and readily repeatable initial tensioning of limb girth adjustment of outer constraint layer.

b) Construction of, or modification to, all forms of below-the-neck nuclear, biological, and chemical (NBC) protective equipment and protective hoods associated with respirator use.

c) Validation of basic ideas for improvement of current generation chemical defense (CD) respirators.

LABORATORY FACILITY REQUIREMENTS

Personnel

Supervisor-Technician

One person who is familiar with all forms of aircrew PPE, PPE design, operation, test, and servicing requirements would be involved in hands-on fabrication of items. This person would also act as supervisor of the laboratory and all lab personnel. Knowledge of basic garment pattern drafting techniques, garment construction, and sizing techniques, including use of adhesives and polymeric materials for pressure garment application is required. The ability to interpret ideas submitted by scientific and technical staff and to translate basic ideas to the equipment production stage is essential. A basic knowledge of fabric and allied materials properties, as well as associated test procedures, is desirable.

Seamstresses-Tailors

Two persons who are experienced in machine sewing of precision garments are required. The ability to interpret clothing patterns and garment assembly instructional data, to cut component pattern parts to precision templates and to construct complete garments to instructions and/or sealed samples. This work involves use of adhesives in the construction of pressure-holding garments and willingness to undertake this type of work is essential. Experience in use of adhesives for garment construction is desirable although on-the-job training will be provided.

Space and Equipment

General

a) A laboratory space approximately 13.72 m x 6.71 m x 3.05 m (45 ft by 22 ft by 10 ft) high is required to house essential equipment.

b) Natural lighting (windows) on at least one wall of the facility is required.

c) Space should be air conditioned; the need for humidity control should be considered.

d) Good artificial lighting throughout the space is required, with supplemental lighting in discrete work areas.

e) Consideration should be given to the provision and proper location of doors to meet emergency fire evacuation requirements.

f) Laboratory should be sufficiently isolated from adjacent office and laboratory areas to ensure that the noise of the heavy-duty sewing machines, etc., is not a disturbance factor.

Support Services

a) Electrical power adequate for lighting and equipment operation (to be determined).

b) Hot and cold water supply (and drainage) for lab sink, wash basin, and shower unit.

c) Compressed air (medical grade) supply with appropriate regulators for garment test inflation.

d) Oxygen supply to appropriate test cabinets/panels.

e) Telephone service.

Furnishings and Fixtures

a) Changing and shower cubicles (one each) with clothing locker.

b) Large laboratory sink with adjacent drain board.

c) Lavatory and towel dispenser.

d) Metal solvent cabinet for storage of flammable chemicals.

e) Fabric layout table, approximately 4.57 m x 1.37 m (15 ft by 4.5 ft), with Formica (or equivalent) surface.

f) Glueing table and fume exhaust arrangement; table with inert impermeable surface, approximately 2.43 m x 1.22 m (8 ft by 4 ft), located under a flexible-duct fume extraction system.

g) Cabinets for pattern storage.

h) Racking for storage of rolls of fabric.

i) Garment storage racks.

j) Office area for supervisor/technician.

k) Appropriately located fire extinguishers.

Plant Machinery

a) Standard and special-purpose sewing machines. Types and numbers of machines remain to be defined; however, requirements include: an overlock machine, a blindstitch machine, and light- and heavy-duty flat-bed sewing machines. All machines will require motors, stands, and illumination.

b) Laboratory vacuum-forming machine with capability of forming deep-draw items such as respirator visors from polycarbonate and similar polymeric sheet material of up to 0.24 cm (3/32 in.) thickness.

c) Radio frequency (RF) welding machine (tentative).

d) Press-stud assembly punch or machine with appropriate dies.

Miscellaneous Expendable Supplies

Anticipated expendable supplies required for initial operation of laboratory facility are:

Stock of relevant fabrics

Heat cutting/sealing boards

Heat cutting/sealing "knives"

Tailor's shears, pinking shears

Measuring tapes, rules, Tailor's T-squares, set squares, French curves

Line-length measuring wheel

Set of standard drawing instruments

Variety of adhesives and solvents

Adhesive applicators and brushes; adhesive containers

Adhesive seam rollers

Wood block and head formers to support adhesive work

Sealing tapes, webbings, special-purpose tapes

Selection of press-studs, buckles, connectors, etc.

Range of hole punches for fabrics

Thread and sewing wax

Stock of standard and gas-tight fasteners (zippers, Velcro)

Garment-service supply connectors, spouts

Rolls of pattern card, standard drawing paper

Pattern-transfer "pricking" wheel

Tailor's chalk, French chalk

COST ESTIMATE

A preliminary estimate of costs is based on the assumption that appropriate laboratory space (approximately 13.72 m x 6.71 m x 3.05 m (45 ft by 22 ft by 10 ft high)), with adequate air conditioning; water, electrical and clean air supplies, and oxygen services is available onsite. A detailed analysis of estimated costs for set-up of the proposed laboratory facility is attached (Table B-1); a schematic diagram of the laboratory is also attached (Fig. B-1).

TABLE B-1. PRELIMINARY COST ESTIMATE

Budget item	Cost ($)
Sewing machines 4 heavy-duty, specialized machines motors, support stands, lights	6,000
Vacuum-forming machine	12,000
RF welding machine and installation	15,000
Fabric layout/cutting table	500
Glueing table and fume exhaust system	2,100
Solvent storage cabinet	1,000
Pattern storage cabinet	150
Racks for storage of fabric rolls	150
Racks for storage of garments	150
Changing cubicle - construction, installation	200
Plumbing purchase, installation (sink, shower, drainage)	800
Electrical power - supply, installation	1,500
Clean air - supply, piping, regulators, etc.	500
Oxygen - supply, piping, instrumented control panel	1,000
Supervisor's office area equipment	200
Expendable supplies includes 25-m rolls of 10 fabric stocks	4,500
Approximate Total	$45,750

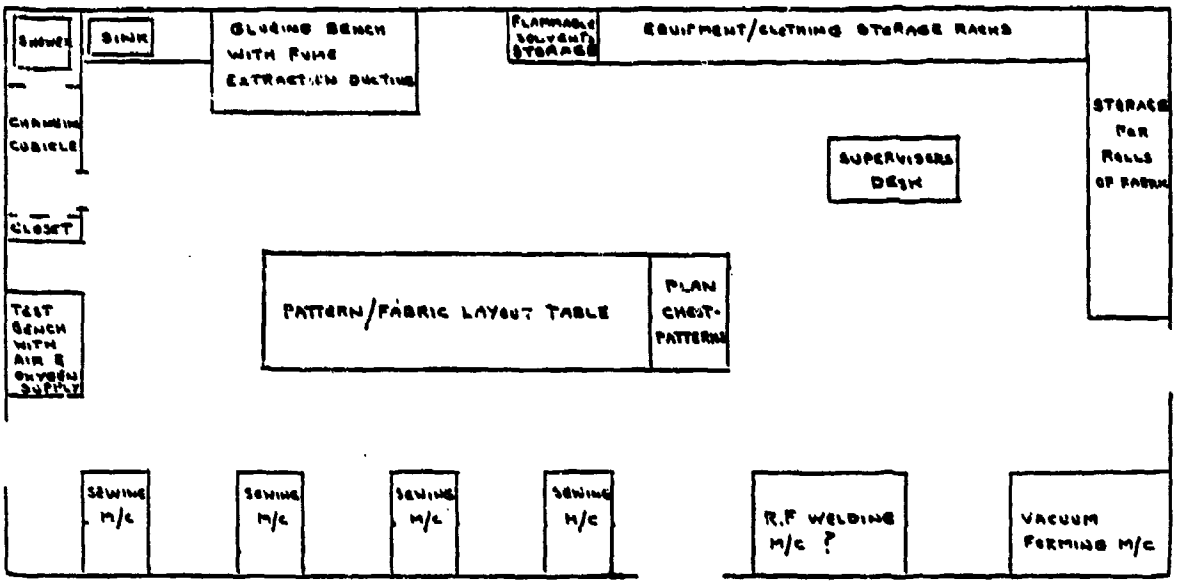

Figure B-1. Schematic layout of outline proposals for an in-house facility for the modification and production of developmental aircrew personal protective equipment.

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